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The Low Emittance Design Study for CANDLE Synchrotron Light Source Project

G. Zanyan

CANDLE Synchrotron Research Institute, 0040 Yerevan, Armenia

E-mail: zanyan@asls.candle.am

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Abstract. To improve the CANDLE synchrotron light source brightness, new low emittance lattices for CANDLE booster and storage ring have been studied. New lattice configurations take into account recent developments in multi-bend achromat design and advanced magnet fabrication technology. The main design considerations, linear and non-linear beam dynamics for booster and storage ring modified lattices are presented.

Keywords: storage ring, booster, lattice, emittance, beam dynamics.

Introduction

The CANDLE – Center for the Advancement of Natural Discoveries Using Light Emission – is a 3 GeV energy synchrotron light source project for advanced researches in the fields of life, materials and environmental sciences [1]. The facility design, based on the double band achromat lattice, provides the horizontal beam emittance of 8.4 nm. Recently, for the new storage ring projects (MAX-4, Sirius) [2-4] and upgrade of existing facilities (DIAMOND, ESRF, SLS, APS, ELETTRA etc.) [5,6] low emittance lattice designs have beam proposed aiming at emittance reduction by 1-2 orders of magnitude (up to sub nm range) to enable the diffraction limited experiments with synchrotron radiation. The main approaches for low emittance lattice design are the use of Multi Bend Achromat (MBA) type cells, bending magnets with longitudinal gradient fields and damping wigglers.

Based on the recent developments in design consideration and magnet technology, new low emittance lattices for the booster and storage ring of CANDLE synchrotron light source project were studied. The booster new lattice design [7] is based on compact combine-function bending magnets enabling a reduction of beam emittance at full energy by factor of 4. The new lattice provides a reliable beam dynamics during the injection to storage ring and facility top-up operation. The low emittance lattice design for CANDLE [8] storage ring, using compact combined function magnets in double band achromat cell and keeping the ring original circumference, provides the reduction of beam emittance to 5.2 nm with sufficient dynamic and momentum acceptances. For further emittance reduction, a four-bend achromat (4BA) lattice was studied to reduce the beam emittance to 1 nm level. This paper summarizes the main results of CANDLE booster and storage ring lattices design, including the nonlinear beam dynamics aspects.

1. Low Emittance Booster

The injection system of CANDLE storage ring [1] is 100 MeV linac and 3GeV full energy booster. The design lattice of booster consists of four-fold symmetry periods with 2.6 m long straight sections between them. Two of the straight sections are occupied by RF-cavities and the others are required for beam injection and extraction.

For the continuous injection into the storage ring, it is necessary to have small emittance in booster at full energy. The lattice of CANDLE booster provides 75 nm-rad horizontal emittance which makes the top-up injection impossible. One of the main tasks of low emittance upgrade was to design a new low emittance booster lattice, which would provide clean and continuous injection to storage ring. The new 192 m long lattice consists of four symmetric arcs separated by 5m long straight sections. Each arc has two matching cells and 9 FODO cells, consisting of two combined-function magnets (with integrated quadrupole and sextupole components) separated by 0.55 m long drift. The straight sections provide zero dispersion which is required for the injection and RF systems. For the correction of transverse chromaticities and provision of sufficient dynamic aperture additional defocusing sextupoles are installed at the end of each FODO cell (Fig. 1).

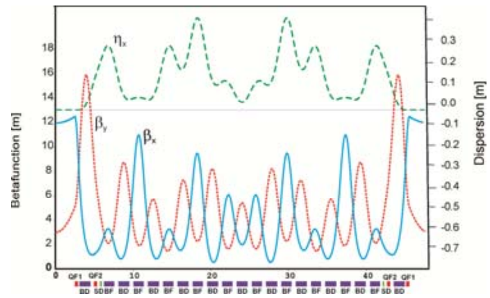

Fig. 1. Beta functions and dispersion in one quadrant of low emittance booster lattice.

The lattice with above mentioned modifications provides about 4 times lower emittance when compared with the original booster lattice. Main parameters of booster original and new low emittance lattices are presented in Table 1.

Table 1: Main parameters of CANDLE booster original and new low emittance lattices

Parameter	Original lat.	Low emit lat.
Injection Energy (MeV)	100	100
Extraction Energy (GeV)	3	3
Emittance (nm rad)	74.9	19.54
Circumference (m)	192	192
Lattice type	FODO	FODO
Number of periods	4	4
Straight section length (m)	2.6	5
Max. betafunction (hor./vert.)(m)	8.5/ 12.2	12.4/ 16.1
Natural chrom. (hor./vert.)	-11.19/ -8.63	-19/ -14.2
Betatron tunes (hor./vert.)	7.6/7.4	13.44/8.35

The detailed description of new booster lattice is given in Ref. [7].

2. Low emittance storage ring

The design lattice of CANDLE storage ring with 216 m circumferences, consisting of 16 Double-Bend Achromatic (DBA) cells, provides 8.4 nm rad beam emittance. Taking into account the well-known scaling of the beam emittance ε with energy E and number N_b of lattice bending magnets, $\varepsilon \sim E^2 N_b^{-3}$, two approaches of beam emittance reduction were considered.

First of all it was attempted to change the original lattice by considering the usage of more compact magnets with combined fields, thus, increasing the number of magnets, without changing the circumference of the machine and the DBA type of cells [8]. The proposed new lattice contains 24 DBA cells, consisting of two combined function bending and two quadrupole magnets (Fig.2 a)). This new design of storage ring lattice allows reducing the beam emittance up to 5.19 nm rad. Despite the luck of flexibility in the presenting lattice it was possible to achieve rather large on and off-momentum dynamic apertures at the center of straight section (Fig. 2 b)).

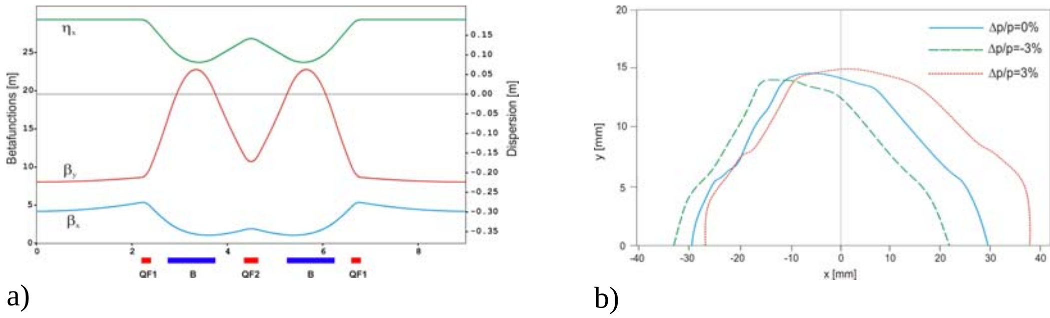

Fig. 2. a) beta functions and dispersion in one period of low emittance DBA lattice
b) on and off-momentum dynamic apertures of low emittance DBA lattice

The optimization of sextupolar terms done by OPA code [9] allowed to keep energy and amplitude dependent tune shifts low enough not to cross dangerous resonances up to third order in the range of 3% energy deviation and amplitudes corresponding to dynamic aperture (Fig. 3).

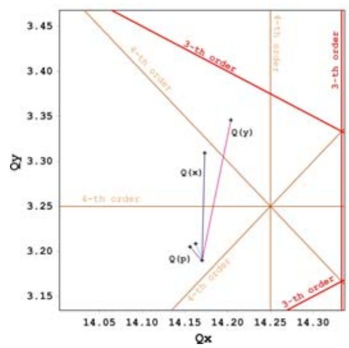

Fig. 3. Betatron tune dependences on energy deviation and
on horizontal and vertical amplitudes in resonance diagram.

Next, we have studied the possibility of further emittance reduction using MBA lattices. Several types of MBA lattices with different numbers of bending magnets per cell were considered. It was aimed to keep the number of straight sections not less than it is in the original lattice. Finally, the search ended up on 4BA cell solution, which provides about 1.1 nm beam emittance with moderate values of magnet parameters. The new lattice is composed of 16 4BA cells separated by 4 m long straight sections. In each cell the horizontal focusing is performed by 7 quadrupole magnets and the vertical focusing - by 2 quadrupole magnets and 4 combined-function bending magnets together matching the values of optical functions in middle dipoles close to values providing Theoretical Minimum Emittance cell condition (Fig. 4 a)). Since quadrupole components of magnets, providing such small value of emittance, are large, leading to high values of chromaticities, strong sextupole components of combined function magnets and one additional family of sextupole magnets are used for chromaticity correction. However, these strong sextupole fields become the reason for lowered dynamic aperture as shown in Fig. 4 b).

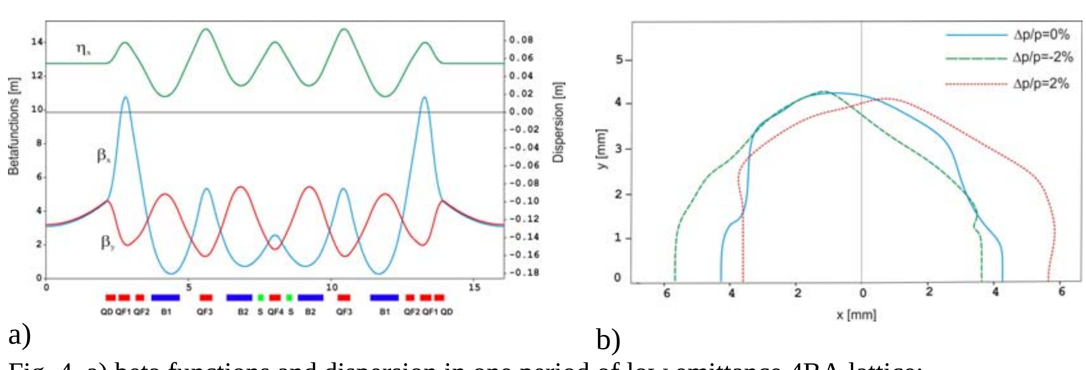

Fig. 4. a) beta functions and dispersion in one period of low emittance 4BA lattice;
b) on and off-momentum dynamic apertures of low emittance 4BA lattice

Although the obtained dynamic aperture is still acceptable from the beam dynamics point of view, taking into account the small value of emittance, however, it necessitates the development of more precise injection schemes, which are planned to be made in future works.

In Fig. 5 betatron tune dependences on energy in 2% deviation range and on horizontal and vertical amplitudes in a range allowed by dynamic aperture are shown.

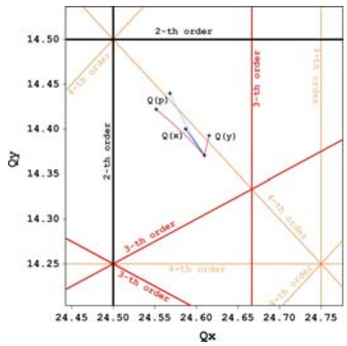

Fig. 5. Betatron tune dependences on energy deviation and on horizontal and vertical amplitudes in resonance diagram.

Note, that the ring circumference for this solution, however, is longer by 42 m as compared with the original CANDLE lattice, which is the price to pay for beam emittance reduction and keeping the number of straight sections unchanged.

In Table 2 the main parameters of CANDLE original storage ring and new low emittance lattices are presented.

Table 2. The main parameters of CANDLE original storage ring, new low emittance DBA and 4BA lattices

Parameter	Original	DBA	4BA
Circumference (m)	216	216	258
Number of periods	16	24	16
Straight section length (m)	4.8	4.4	4.2
Energy (GeV)	3	3	3
Emittance (nm rad)	8.4	5.2	1.1
Energy spread (%)	0.1	0.15	0.1
Momentum acceptance (%)	2.4	2.1	3.9
Natural chrom. (hor./vert.)	-18.91/ -14.86	-13.64/ -24.27	-38.27/ -26.04
Betatron tunes (hor./vert.)	13.2/ 4.26	14.17/3.19	24.61/14.37

Summary

This paper summarizes the results of new low emittance lattice options development study for carried out CANDLE light source booster and storage ring.

A new design of booster lattice, based on implementation of combined function bending magnets, is proposed, which allows reducing the beam emittance by factor of 4 at full energy as compared with the original booster lattice, granting a reliable beam dynamics during the injection and facility top-up operation.

Two options of low emittance lattices for CANDLE storage ring were considered. In the first solution the emittance was reduced by increasing the number of bending magnets in the lattice keeping the circumference of the ring and the type of lattice unchanged. This could be done by using compact combined-function magnets taking into account the recent achievements in the field of magnet technologies. As a second option the implementation of four-band achromat lattice was studied, which allows the beam emittance reduction up to 1.1 nm. In comparison with the original lattice the proposed one is characterized by lowered dynamic aperture, which necessitates the development of more precise injection schemes.

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