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Low emittance lattice for the storage ring of the Turkish Light Source Facility TURKAY*

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Abstract: The TAC (Turkish Accelerator Center) project aims to build an accelerator center in Turkey. The first stage of the project is to construct an Infra-Red Free Electron Laser (IR-FEL) facility. The second stage is to build a synchrotron radiation facility named TURKAY, which is a third generation synchrotron radiation light source that aims to achieve a high brilliance photon beam from a low emittance electron beam at 3 GeV. The electron beam parameters are highly dependent on the magnetic lattice of the storage ring. In this paper a low emittance storage ring for TURKAY is proposed and the beam dynamic properties of the magnetic lattice are investigated.

Key words: TURKAY, storage ring, beam dynamics, synchrotron radiation

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1 Introduction

The Turkish Accelerator Center (TAC) project has been proposed to build an accelerator center in Turkey in order to use accelerators and accelerator based light sources for research and development (R&D) in Turkey and the surrounding region [1]. The first phase of TAC, which started construction in 2010, is building an Infra-Red Free Electron Laser (IR-FEL) facility covering the range of 3–250 microns [2]. The second stage is proposed to be a Synchrotron Radiation (SR) facility named TURKAY, which is a third generation light source that aims to achieve a high brilliance photon beam from a low emittance electron beam [3, 4]. The project is now entering its detailed design phase, after the completion of the conceptual design report.

Third generation light sources can be classified as low energy, intermediate energy (2–4 GeV) and high energy light sources. The disadvantage of low energy sources is that high quality X-ray beams cannot be produced. In contrast to the cost of low energy sources, however, high energy sources are quite expensive. Thermal loading in the beam line equipment is another problem for high energy light sources. In recent decades, intermediate and high brightness light sources have become the more preferred light sources. Photon energy ranging from a few eV to 100 keV can be produced by the use of insertion device technology. Therefore, intermediate energy light sources, which have a relatively low construction budget, can provide a relatively wide photon energy range. Based on these considerations and on the requirements of synchrotron radiation users, as gathered from the light source user meetings arranged by the TAC project, the main goals of TURKAY have been determined. It has been decided to reach a very low emittance value at 3 GeV electron beam energy and relatively short storage ring circumference. The emittance value of the storage ring should be below 1 nm·rad.

2 Optical structure of storage ring

One of the important parameters of a light source is the brilliance, which is defined as the number of photons emitted per second, per photon energy bandwidth, per solid angle and per unit source size. The brilliance can be expressed as [5, 6]

$$B=\frac{\mathrm{d}N/\mathrm{d}t}{4\pi^2\sigma_x\sigma_{x'}\sigma_y\sigma_{y'}\dfrac{\Delta\omega}{\omega}}\approx\frac{flux}{4\pi^2K\varepsilon_x^2}, \tag{1}$$

where K is the coupling constant and ε_x is the natural emittance. The flux depends on the beam current, undulator period and undulator deflection parameter. So, the brilliance of a storage ring is strongly related to the natural emittance and in order to maximize it, the horizontal and vertical emittances must be as small as possible.

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Emittance is defined as the area of the phase ellipse and is characteristic of a storage ring. The emittance is correlated to the beam cross section via

$$\sigma_{x,y}=\sqrt{\varepsilon_{x,y}\beta_{x,y}}, \tag{2}$$

where $\beta_{x,y}$ is one of the Twiss parameters and is a position dependent quantity which describes the beam focusing at that point.

In a storage ring, the optical structure is the basic part of the machine, and the main parameters of the stored beam are determined by the magnetic lattice. The main consideration of the magnetic lattice is to achieve a low emittance electron beam in order to obtain a high brilliance photon beam.

The zero current natural emittance in an electron storage ring is governed by

$$\varepsilon_0\sim\frac{E^2}{N_{\rm s}^3N_{\rm d}^3}, \tag{3}$$

where E is the electron beam energy, $N_{\rm s}$ is the number of sectors and $N_{\rm d}$ is the number of bending magnets [7]. Based on this equation, it was decided to work on a multi-bend lattice.

To get a low-emittance beam, a four-bending-magnet lattice structure is designed for the main cell. The main cell consists of 4 bending magnets and 4 different type (16) quadrupole magnets. Fig. 1 shows the betatron and dispersion functions of the main cell.

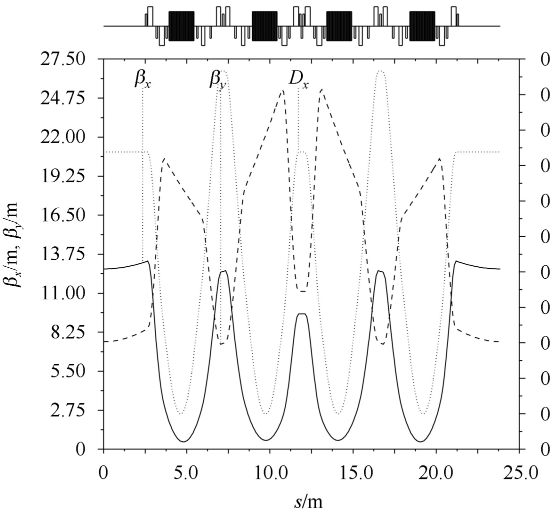

Fig. 1. Betatron and dispersion functions in the main cell for finite dispersion mode.

The ring has finite dispersion in the straight sections and its emittance value is 0.51 nm·rad. The lattice optics can be easily tuned to an achromatic lattice by adjusting the strength of the quadrupoles. In the achromatic case the emittance is 0.93 nm·rad.

The storage ring is composed of 20 main cells and its circumference is 477 m. The working point is chosen where the resonance driving terms and tune shifts are as small as possible. 7 families of sextupoles are used to correct chromaticity and to compensate for nonlinearities. In total, there are 80 bending magnets, 320 quadrupoles and 460 sextupoles in the whole ring. The length of the straight sections is considered to be 5 m for the RF cavity, insertion devices and injection requirements. There are 20 straight sections; two of them for injection and RF cavity and the rest for undulators. The main consideration for the number of bending magnets and sections comes from the limitations of the circumference and budget. The bending magnets are 1.5 m long and the magnetic field in the bending magnets is 0.52 T. The advantage of the low field of the bending magnets is low RF power requirement.

The main parameters of the storage ring are listed in Table 1 for finite dispersion and achromatic modes. OPA [8], MADX [9] and BEAMOPTICS [10] codes are used to design the magnetic lattice of the storage ring.

Table 1. The main parameters of the storage ring.

parameters	F. D. mode	Achr. mode
energy/GeV	3.0	3.0
circumference/m	477	477
beam current/mA	450	450
H. Emittance/(nm·rad)	0.51	0.93
V. Emittance/(nm·rad)	0.0051	0.0090
energy loss/part./turn/keV	375.1	375.1
Max.β_x/m	12.7	15.4
Max.β_y/m	25.3	28.1
β_x in the mid. of str. sec./m	12.7	15.4
β_y in the mid. of str. sec./m	7.5	9.8
D_x in the mid. of str. sec./m	0.09	0.00
betatron Tunes Q_x/Q_y	31.19/6.15	36.24/6.18
natural chromaticity ξ_x/ξ_y	$-70/-38$	$-84/-43$
corrected chromaticity ξ_x/ξ_y	0.0/0.0	0.0/0.0
number of straight sections	20	20
length of straight section/m	5	5
RMS energy spread/(%)	0.05	0.058
damping time (H/V/L)/ms	26.9/26.9/13.4	25.5/25.5/12.7
RF voltage/MV	3.5	3.5
RF frequency/MHz	500	500
harmonic number	795	795
bunch charge/nC	1	1
RMS bunch length/mm	2.1	2.1
momentum acceptance(%)	4.8	5.6
Mom. compaction factor	0.00032	0.00025
coupling(%)	1	1
Touschek lifetime/h	11.0	18.6
radiation integrals		
I1/m	0.156842671	0.123663616
I2/m^{-1}	0.328902260	0.328902260
I3/m^{-2}	0.017216856	0.017216856
I4/m^{-1}	0.0	0.0
I5/m^{-1}	0.00001288	0.0000248191

In a low emittance lattice, strong focusing leads to high chromaticity. Therefore, strong sextupoles are needed to correct the natural chromaticity that limits the dynamic aperture. Two sextupoles are used for chromaticity corrections and those sextupoles lead to tune shift. They should be placed in suitable places to minimize the nonlinear effects. One of them ($k_2 > 0$) is located at the beginning of the lattice where β_x is large and β_y is small. The second ($k_2 < 0$) is located where the point β_y is large and β_x is small. The purpose of the other 5 sextupoles are to compensate for the nonlinear effects of the chromatic sextupoles. Their locations and strengths are determined by the use of OPA simulation code and the goals are to keep the dynamic aperture as large as possible and to keep the particles away from the resonance lines.

3 Nonlinear beam dynamics

The dynamic aperture is the stable transverse area for the particle in which it can execute its oscillations safely without getting defocused or lost. Storage rings require a large dynamic aperture in order to achieve good injection efficiency and good beam lifetime. Large dynamic aperture is also an indication of high beam stability. ELEGANT code [11] is used to determine dynamic aperture. The dynamic aperture for different momentum offsets and for several magnet error situations are demonstrated in Figs. 2 and 3, respectively. It can be seen from the figures that the dynamic aperture is large enough for such a low emittance ring and the effect of the magnet error is not large.

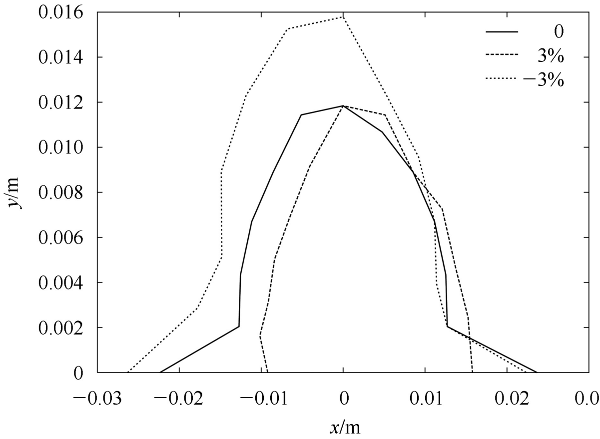

Fig. 2. Dynamic aperture of storage ring for different momentum offsets (1024 turns, magnet error is zero).

Frequency Map Analysis (FMA) [12] is a numerical method for understanding the effect of resonance on the dynamic aperture. For this purpose diffusion rate

$$D=\log_{10}\sqrt{\Delta\nu_x^2+\Delta\nu_y^2}, \tag{4}$$

can be used as a stability index [13]. $\Delta\nu_x$ and $\Delta\nu_y$ are the transverse tune shifts of surviving particles in tracking. Fig. 4 shows the dynamic aperture from FMA results of single particle tracking without synchrotron radiation.

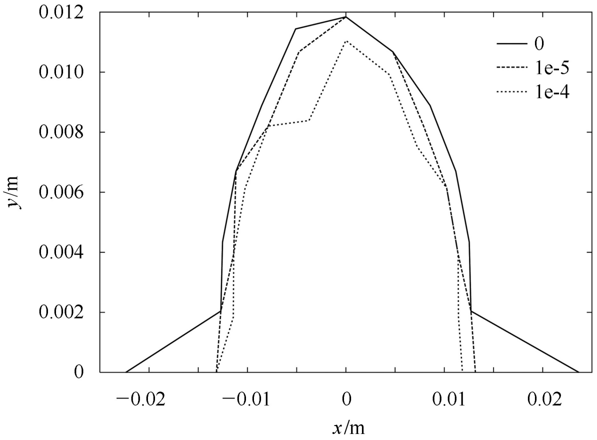

Fig. 3. Dynamic aperture of storage ring for different magnet errors (1024 turns, momentum offset is zero).

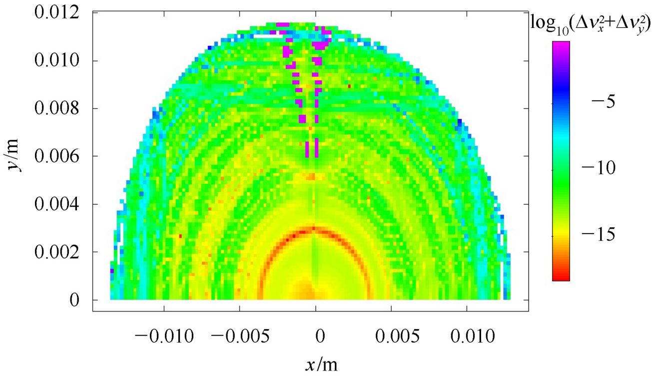

Fig. 4. Effect of resonance on dynamical aperture from FMA.

One of the important nonlinearity issues for a low emittance storage ring is intrabeam scattering, which is the Coulomb scattering within a beam, which usually increases the beam emittance. The horizontal beam emittance and relative energy spread with intrabeam scattering are [14, 15]

$$\varepsilon_x=\frac{T_x}{T_x-\tau_x}\varepsilon_{x0}, \tag{5}$$

$$\sigma_\delta=\frac{T_x}{T_x-\tau_p}\sigma_{\delta 0}, \tag{6}$$

where T_x and T_p are the horizontal and longitudinal intrabeam scattering growth rates, τ_x and τ_p are the horizontal and longitudinal radiation damping times and ε_{x0} and $\sigma_{\delta 0}$ are the zero current horizontal emittance and relative energy spread.

The emittance value with intrabeam scattering is calculated using ELEGANT code. The obtained emittance value is 0.70 nmrad for 450 mA average beam current, 3.5 MV RF voltage and 500 MHz RF frequency. This emittance value is used in the brilliance and flux density calculations described in the next section.

Another nonlinear beam dynamics effect is the Touschek lifetime. This is the limitation due to Touschek scattering, which describes the collision of two electrons inside a bunch with transfer of transverse momentum into longitudinal momentum. According to the simulation results on the storage ring, the Touschek lifetime is 11.0 h. It is planned to operate the machine in top-up operation mode, which aims to maintain a steady current in a storage ring by periodically injecting small amounts of current.

4 Radiation properties

The radiation spectrum is investigated by looking at some existing or planned insertion devices from other synchrotron radiation facilities [16], with some slight changes. The amended undulator parameters are sown in Table 2.

Table 2. Main parameters of the insertion devices.

parameters	CU18	SU15	IU28	U90
period length/cm	1.8	1.5	2.8	9
number of period	222	67	142	44
min. gap/mm	5	5.6	7	35
K_{ymax}	2.25	2.10	2.35	10
length/m	4.0	1.005	4.0	4.0
photon energy/keV	1.4–20	1.8–23	0.8–12	0.1–3

IU28 is an in-vacuum undulator with 28 mm period length. The CU18 cryogenic permanent magnet undulator can provide brilliance value up to 1.5×10^{21} photon $\mathrm{s}^{-1}\mathrm{mrad}^{-2}$ per 0.1% BW. SU15 is a superconducting undulator with period length of 15 mm, which can provide photons in the energy range 1.4–20 keV. U90 is a conventional permanent magnet undulator with period length 9 cm. The brilliance is calculated with SPECTRA code [17] and the obtained graphic is presented in Fig. 5.

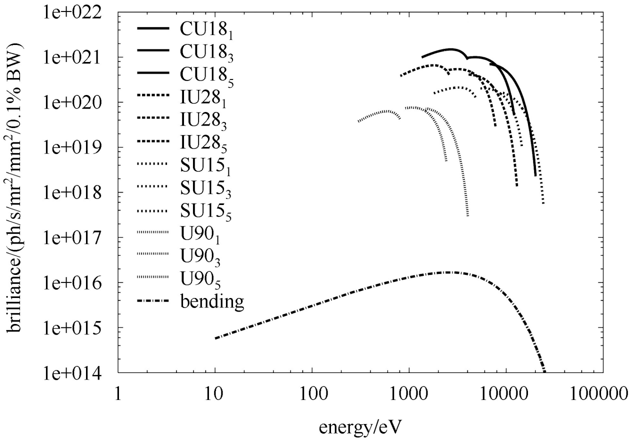

Fig. 5. Brilliance spectrum.

5 Conclusion

The storage ring for TURKAY has been designed and its storage ring parameters presented. 0.51 nm rad emittance value is achieved with a relatively short circumference. The nonlinear effects are also investigated. It is seen that the dynamic aperture values are large enough for such a low emittance ring. A brilliance value of more than 10^{21} photon/s/%0.1BW/mm^2/mrad^2 can be provided by these storage ring parameters with appropriate undulators.

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