DESIGN OF A SMALL EMITTANCE ELECTRON STORAGE RING FOR HIGH BRIGHTNESS VUV RADIATION

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Abstract: A small emittance of 3.5 nmrad at 1.5 GeV is obtained in a design of an electron storage ring composed of a TBA lattice structure with 14 superperiod. An appropriate selection of betatron tune together with compensation sextupoles in dispersion free region results in a large dynamic aperture. Tune shift and distortion of beta function induced by wigglers are corrected with four kinds of quadrupoles locally for each wiggler.

Introduction

Here is presented a design study of an electron storage ring with a small emittance beam for an intense VUV radiation. The ring operated at 1.5 GeV (γ=3000) consists of a TBA lattice structure with a 14 symmetry and a circumference of 241.4 m. The radiation is provided by 12 wigglers and 14 bending magnets.

In designing a small emittance ring composed many wigglers there are three fundamental probles; 1) how to realize a small emittance with a large dynamic aperture, 2) how to cope with the effects of wigglers , and 3) how to suppress various instabilities at a high beam current. The former two subjects, discussed in the following, are problem of one electron stability and determined by the lattice design.

Requirement for electron beam

The intensity of wiggler radiation is highly concentrated on the radiation axis, and the highest brightness of the radiation can be obtained in the narrowest bandwidth of peaked radiation spectrum. The bandwidth of the k-th harmonic is determined by

$$\frac{\Delta\lambda}{\lambda_k} = \frac{1}{kN_w}, \quad \frac{\Delta\lambda}{\lambda_k} \approx (\gamma\Delta\theta)^2 \qquad (1)$$

where N_w is the number of wiggler period, and $\Delta\theta$ the angle from the radiation axis. For a 5 m wiggler we can have $N_w \cong 100$ and then $\Delta\lambda/\lambda_k \cong 3\times10^{-3}$ for k=3. So the angle should be $\Delta\theta < 20\ \mu$rad, or the slit of a monochrometer should be $2L\Delta\theta < 0.8$ mm at a distance of L=20 m.

Broadening of the bandwidth due to the size $\sigma_{x,y}$ and divergence $\sigma'_{x,y}$ of the electron beam should be sufficiently small compared with the above bandwidth. This sets the following conditions on the electron beam ($\varepsilon_{x,y}$; emittance),

$$\sigma_{x,y} \lesssim \frac{L\Delta\theta}{2} \approx 0.2\ \text{mm}, \quad \sigma'_{x,y} \lesssim \frac{\Delta\theta}{2} \approx 10\ \mu\text{rad}$$
$$\varepsilon_{x,y} \lesssim 2\ \text{nmrad} \qquad (2)$$

The radiation has its own emittance $\varepsilon_{ph} = \lambda/4\pi$ determined by the uncertainty principle, which is 0.8 nmrad at a wavelength λ=100 A. Thus the reduction of electron beam emittance to the above value is still useful.

Lattice

Such a small emittance beam can be realized by the DBA or TBA structure with a superperiod Ns≥12. Several variations of these structure are shown in Fig.1, among which we have selected the structure C because of the following reasons. Bending magnets of combined function type, which can provide a smaller emittance, are not used because of uneasiness of edge shaping. TBA can provides a smaller emittance than DBA with nearly the same unit cell length. Four kinds of quadrupole magnets are necessary to make a local compensation of beta function and betatron tune which are considerably affected by wigglers at the beam energy.

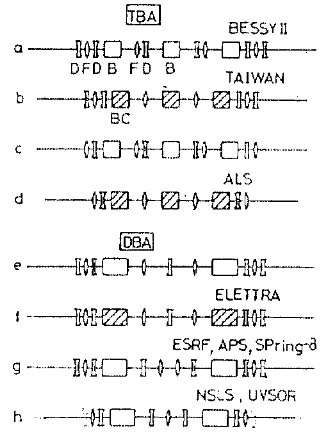

Fig.1
Various type of unit cell for TBA and DBA structure.

Unit cell of the lattice structure is shown in Fig.2. Focusing quadrupoles are separated nearly equally from the side bending magnets to locate the minimun beta function at the center of the bending magnets, which produces the smallest emittance. Bending magnets have an edge angle of 15 deg to reduce the maximum vertical beta. The lattice function and beam size are shown in Fig.3. The lattice function is small and varies slowly along the circumference, which gives a good stability against a change of quadrupole field strength. The strength variation of 1 % induces a 8 % variation of maximum beta, which is very small compared with 150 % in the METRO mode of BESSY.[1] The emittance is 3.5 nmrad, which can be easily increased to 11 nmrad, if necessary, by introducing a small negative dispersion η_x=-0.1 in the long straight section. A small vertical beam size (σ_y=0.02 mm at 10 % coupling) in the center bending magnet may be useful for some users of bending radiation. Lattice parameters are given in Table 1.

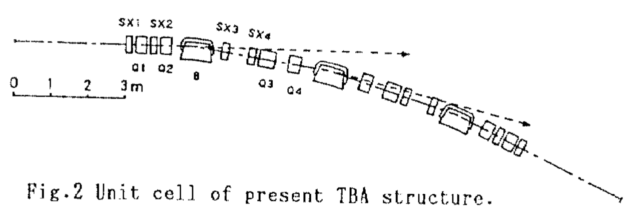

Fig.2 Unit cell of present TBA structure.

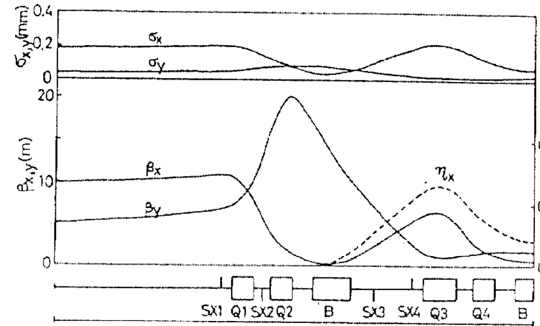

Fig.3
Lattice functions and beam size in a half unit cell.

Table 1 Parameters of electron storage ring

Beam energy	E	1.5	GeV
Circumference	C	241.4	m
Superperiod	N_S	14	
Emittance	ε_x^0	3.5	nmrad
Betatron tune	ν_x/ν_y	17.22/10.20	
Chromaticity	ξ_x/ξ_y	-33.7/-23.9	
Momentum comp. factor	α_p	1.06×10^{-3}	
Radiation loss	U	98.5	keV/turn
Energy spread	σ_E/E	6.08×10^{-4}	
Damping time	$\tau_x/\tau_y/\tau_E$	23.8/24.5/12.5	msec
RF voltage	V_{RF}	1.4	MV
RF frequency	f_{RF}	499.6	MHz
Revolution period	f_0	1.243	MHz
RF bucket height	$\Delta E/E$	3.5	%
Touschek lifetime	$I\tau_T$	5.3	Ah

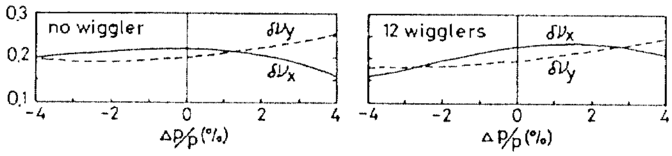

Fig.4 Momentum dependence of the tune.

Dynamic aperture

The chromaticity of the lattice is ξ_x/ξ_y=-33.7/-23.9. To suppress a large tune shift for a large momentum deviation about±3 % and also the head-tail instabilty, the chromaticity is reduced to zero with sextupole magnets installed in dispersion region, while there still remains a little momentum dependence of the tune(see Fig.4). Nonlinear field of the magnets, on the other hand, induces a large amplitude dependent tune shift, which in turn reduces the dynamic aperture drastically. The tune shift, determined by the distortion function of sextupole field, is expressed as[2]

$$\Delta\nu_x = A_{11}x^2/\beta_x^2 + A_{12}y^2/\beta_y^2$$
$$\Delta\nu_y = A_{21}x^2/\beta_x^2 + A_{22}y^2/\beta_y^2 \qquad (3)$$

where Aij's are the coefficients determined by the sextupole fields and beta function. The coefficients become large when the betatron tune satisfies the following condition

$$\nu_x,\ 3\nu_x,\ 2\nu_y \pm \nu_x \approx mN_s \qquad (m\text{:integer}) \quad (4)$$

Figure 5 shows the map of the smallest deviation of ν_x, $3\nu_x$, $2\nu_y\pm\nu_x$ from mNs, together with nonlinear structure resonances up to sixth order. We see the optimum tune is ν_x/ν_y=17.2/10.2.

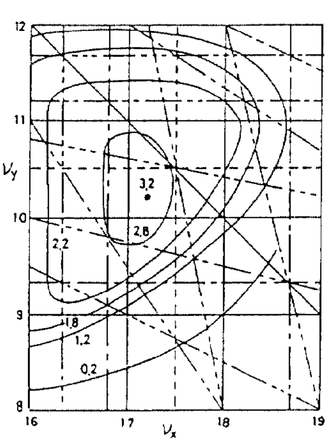

Fig.5 Smallest deviation of ν_x, $3\nu_x$, $2\nu_y\pm\nu_x$ from mNs and nonlinear structure resonances.

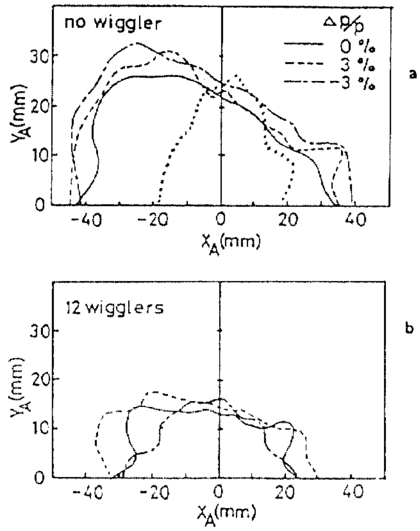

Fig.6 Dynamic aperture tracked 100 turns. Dotted line represents the dynamic aperture without compensation sextupoles.

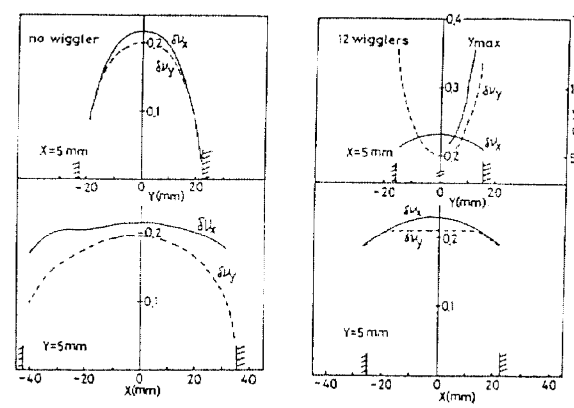

Fig.7
Amplitude dependence of the decimal part of the tune.

The coefficients thus obtained are still as large as |Aij|≤4880, and the dynamic aperture is as small as XA/YA=20/24 mm. Introducing additional sextupoles (compensation sextupoles) in dipersion free region reduces the coefficients to less than 740, and the aperture is expanded as large as XA=-40/34 mm, YA=±23 mm (see Fig.6). Amplitude dependence of the tune is shown in Fig.7. We see that the aperture is determined by a rapid tune shift to integer(or half integer) resonance. Momentum and amplitude dependences of the tune are also shown in the tune diagram together with the third and fourth order resonances (see Fig.8).

Tracking simulation shows that the aperture is wide enough for beam injection. It is noticed that the vertical betatron amplitude is enhanced by the coupling with a large horizontal oscillation amplitude due to the sextupole fields. Tracking simulation for beam injection indicates that allowable angle errors are 1.2 mrad horizontally and vertically for injection betatron amplitude of 10 mm to clear a vertical aperture of ±10 mm at a long straight section.

Effects of wigglers

Four kinds of wigglers (each 3) with a length 4.8 m and a different peak fields 3~9 kG and different periodic lengths 5 ~12 cm are installed randomly in the long straightht sections. Measure of wiggler effects is clearly expressed by the tune shift which is caused by the edge focus of the wiggler;

$$\Delta\nu_y = N_w \lambda_0 \langle\beta_y\rangle / 8\pi\rho_0^2 \qquad (5)$$

where ρ_0 is the orbit curvature corresponding to the peak fields of the wiggler. The shift, proprotinal to the square of bean energy, is considerably large at 1.5 GeV. For instance we have $\Delta\nu_y$=0.032 for ρ_0=5.5 mand $\langle\beta_y\rangle$=5 m.

Wigglers distort beta function considerably, which in turn increases the stopband width of the integer and half integer resonance ($\delta\nu_y$=0.14), and the dynamic aperture is reduced substantially. Wiggler also distort the equilibrium closed orbit, which changes the radiation axis.

Above effects of wigglers can be corrected by quadrupole magnets considerably. In ordinary operation, wiggler fields will be changed freely and independently by radiation users, so the correction should be made locally or independently for each wiggler. Corrections for the tune shift and the distortion of beta function can be made at the same time by using four kinds of quadrupoles adjacent to the wiggler. Beta function before and after the correction for a 9 kG wiggler are shown in Fig.9. Beta function after correction for 12 wigglers are also shown in the figure. Quadrupole field strength necessary for the correction are shown in Fig.10 as a function of. $1/\rho_0^2$. For a gradual change of wiggler field the quadrupole field strength should be varied along the solid

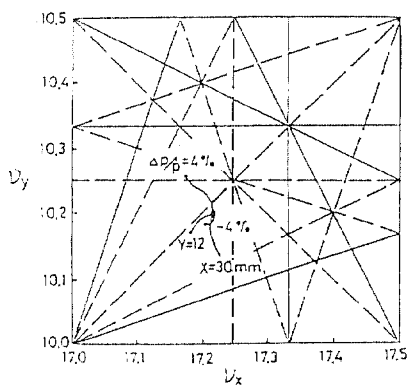

Fig.8 Tune diagram for the operation point, and momentum and amplitude dependence of the tune. Difference resonances are not dangerous.

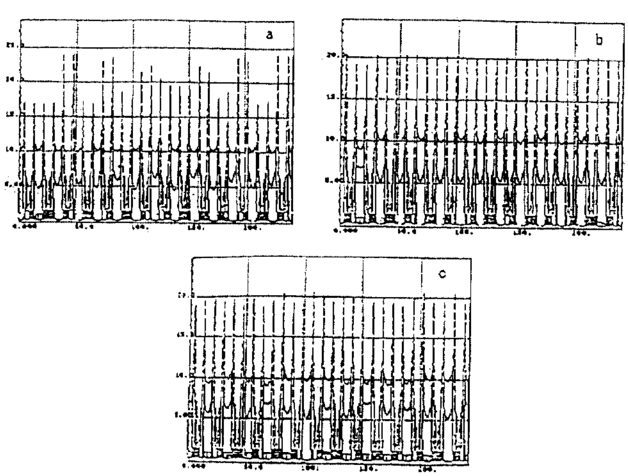

Fig.9 Beta function before (a) and after (b) the correction for a 9 kG wiggler.(c) represents the beta function after the correction for 12 wigglers.

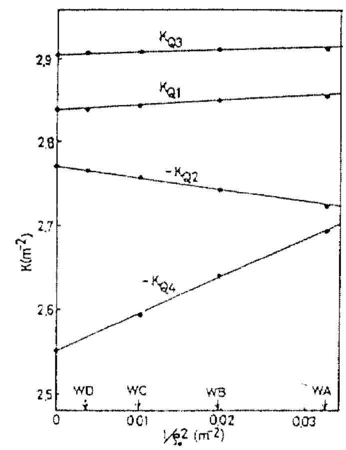

Fig.10
Quadrupole field strength for the correction against four kinds of wigglers WA~WD.

line in the figure. Dynamic aperture after correction for 12 wigglers is as large as XA=±20 mm and YA=±12 mm (see Fig.6), which provides a beam lifetime about 80 h at a pressure of 1 nTorr.

Even with such a correction the closed orbit of the electron beam will change slightly, which shifts the radiation axis of the wiggler, and may be serious for radiation users. Thus it is necessary to make a simultaneous local orbit correction with a feedback loop to four steering magnets adjacent to the wiggler by monitoring the radiation axis with an accuracy less than 0.1 mm. This should be done without disturbing other beam lines(see Fig.11). Vertical and horizontal steering magnets can be installed in each sextupole magnet.

It is known that a wiggler induces the third and fourth order resonances[3]. Tracking simulation, however, does not show any increase of the betatron oscillation amplitude near the fourth order resonance $\delta\nu_y$=0.25(see Fig.7).

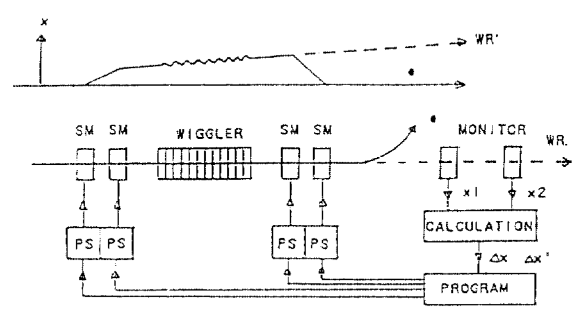

Fig.11 Feed back loop for the correction of radiation axis.

Present study has been performed by the use of computer codes LATTICE, BETA and RACETRACK. The author is grateful to Dr.G.Wüstefeld for valuable discussions at BESSY.

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