

NEXT GENERATION LIGHT SOURCE STORAGE RING AT SPRING-8

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Abstract

We designed a storage ring with an energy of 6 GeV and a circumference of 1436 m. The ring consists of 24 ten-bend achromat cells and has a natural emittance of 83 pm-rad. The circumference is equal to that of a SPring-8 storage ring and the cell length is two times that, which enables the replacement of the existing storage ring with this new one in the SPring-8 tunnel. The horizontal dynamic aperture at the center of a straight section is improved to -6.5 mm and +9.0 mm by changing the sextupole strength for chromaticity correction while maintaining zero chromaticity.

INTRODUCTION

A linac-based XFEL and an ERL are planned to be constructed at many facilities as next-generation light sources. However, no plan exists to construct a storage ring type next-generation light source.

The main problem for ultra low emittance rings is their small dynamic apertures. Large chromaticities due to strong quadrupole magnets and small dispersions need strong sextupole magnets. Strong sextupole magnets result in a small dynamic aperture due to their geometric aberration, making a storage ring with very low emittance infeasible. Even if a storage ring with a large dynamic aperture could be designed, the lifetime of the stored beam would be too short due to the small beam size.

Recently, top-up operation was developed [1, 2]. The beam current is kept constant by repeatedly injecting electron beams at short intervals. This solves the short lifetime problem. Thus, if a large dynamic aperture with low emittance can be obtained, a storage ring type next-generation light source is possible.

We studied the possibility of a storage ring type light source with pm order emittance. We designed a low emittance lattice and improved the dynamic aperture. Emittance growth and lifetime are calculated for different beam conditions.

LATTICE

Increasing the number of dipole magnets to obtain a low emittance lengthens the circumference of storage rings. Construction costs increase with increasing the circumference of rings. To reduce the construction costs, existing facilities can be used. Thus, as an example, we thought to construct a storage ring in a SPring-8 tunnel.

The circumference is 1436 m, equal to that of SPring-8, and we attempted to create the lowest emittance within that restriction. The number of cells of the SPring-8 storage ring is 48, and the cell length is 30 m. Here, we defined the cell as a magnet arrangement with a straight section where an insertion device or an RF cavity can be placed. The cell length of the new ring should be 30 m or an integral multiple of 30 m, which makes using the

existing beamline possible. We chose a 60-m cell length. The arrangement of quadrupole (Q) and sextupole (S) magnets between the dipole magnets was determined in the order Qd, Sd, Qf, Sf, Qf, Sd, and Qd. We designed quadrupole and sextupole magnets with a 40-mm bore diameter. The length of a straight section is 6.6 m, equal to that of SPring-8. With these conditions, 10 dipole magnets can be placed in a cell. The dipole magnets at the ends of each cell are shorter than the other eight magnets for optical matching.

Under these conditions, we designed a very low emittance storage ring. The main parameters are shown in Table 1, and the betatron and dispersion functions in a cell are shown in Fig. 1. The natural emittance is 83 pm, about 1.2 % of original emittance of the SPring-8 storage ring.

Table 1: Main parameters of storage ring.

Parameters	Symbol	Value
Energy	E	6 GeV
Circumference	L	1436 m
Natural emittance	ϵ_{x0}	83 pm-rad
Number of cells	N_c	24
Horizontal tune	ν_x	110.40
Vertical tune	ν_y	27.52
Horizontal chromaticity	ξ_x	-433
Vertical chromaticity	ξ_y	-78
Momentum compaction	α	1.6×10^{-5}
Energy spread	σ_E/E	1.0×10^{-3}

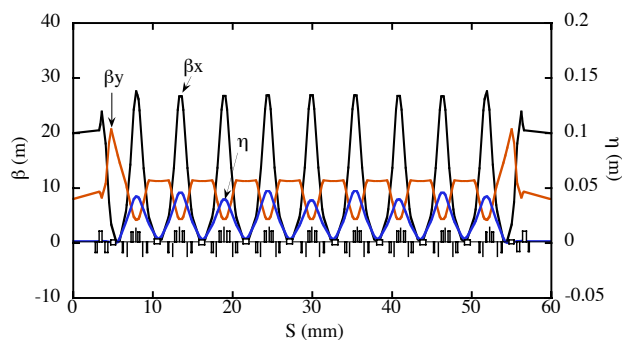


Figure 1: Betatron and dispersion functions in a cell.

DYNAMIC APERTURE

Particle Tracking and Analysis

Particle tracking was done using the tracking code developed at SPring-8 [3]. The dynamic aperture at the center of a straight section obtained by particle tracking is shown by the squares in Fig. 2. The horizontal aperture is only -3.7 and +3.4 mm. The dynamic aperture was analyzed by harmonic expansion of the sextupole field and single resonance approximation.

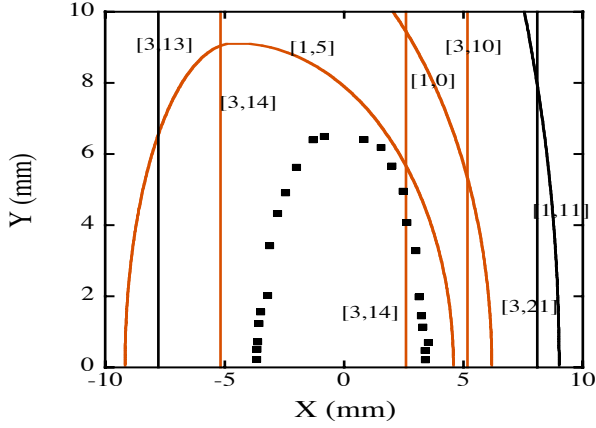


Figure 2: Dynamic aperture obtained by particle tracking and theoretical prediction.

The dynamic aperture due to the first and third order resonances is expressed as [4]

$$(1) \quad v_{xc} = m$$

$$x_A = -\frac{\delta(1+\sqrt{1+432A_{1m}B_{1m}I_y/\delta^2})}{18A_{1m}}, \quad (1)$$

$$x_B = \frac{\delta(2\sqrt{1+432A_{1m}B_{1m}I_y/\delta^2}-1)}{18A_{1m}}, \quad (2)$$

with

$$A_{1m} = \sum_k \frac{(\beta_x^{3/2} S)_k}{48\pi} \cos[\psi_x - v_{xc}\theta + m\theta]_k, \quad (3)$$

$$B_{1m} = \sum_k \frac{(\beta_x^{1/2} \beta_y S)_k}{48\pi} \cos[\psi_x - v_{xc}\theta + m\theta]_k, \quad (4)$$

$$\delta = v_{xc} - m, \quad (5)$$

where v_{xc} is the betatron tune per cell, m is an integer, $I_y = y^2/(2b_y)$, S is the sextupole strength ($S = B''/B\rho$), and

$$\psi_x = \int \frac{ds}{\beta_x}.$$

$$(2) \quad 3v_{xc} = m$$

$$x_A = -\frac{\delta}{3A_{3m}}, \quad (6)$$

$$x_B = \frac{\delta}{6A_{3m}}, \quad (7)$$

with

$$A_{3m} = \sum_k \frac{(\beta_x^{3/2} S)_k}{48\pi} \cos[3(\psi_x - v_{xc}\theta) + m\theta]_k, \quad (8)$$

$$\delta = v_{xc} - m/3. \quad (9)$$

The boundaries of the stable regions were calculated using the above equations and are shown in Fig. 2 by the solid lines. The smallest boundary in the horizontal direction is [3, 14], where, in the notation of $[i, m]$, i is the order of resonance, and m is the harmonic number. The second smallest is [1, 5], followed by [3, 10], [1, 0], etc. The [3, 14] and [1, 5] resonances clearly dominate the dynamic aperture. The [3, 10] and [1, 0] boundaries also seem to affect the size of the stable region.

Improvement

Terms [3, 14], [1, 5], [3, 10] and [1, 0] should be

suppressed, especially [3, 14] and [1, 5]. To suppress these components, the absolute values of $A_{3,14}$, $A_{1,5}$, $A_{3,10}$, and $A_{1,0}$ should be decreased simultaneously. We calculated the harmonic components and found that $A_{1,5}$ and $A_{3,14}$ have negative values, and $A_{1,0}$ and $A_{3,10}$ have positive values.

A function excluding the sextupole magnets and removing the summation in Eqs. (3) and (8) is

$$a_{im}(s) = \frac{\beta_x^{3/2}(s)}{48\pi} \cos\{i[\psi_x(s) - v_{xc}\theta(s)] + m\theta(s)\}, \quad (10)$$

$(i = 1, 3)$.

Functions $a_{1,5}$, $a_{3,14}$, $a_{3,10}$, and $a_{1,0}$ are shown in Fig. 3. Since $A_{1,5}$ and $A_{3,14}$ have negative values, and $A_{3,10}$ and $A_{1,0}$ have positive values, the absolute values of all four harmonics decrease if we place a defocusing sextupole of appropriate strength at position A.

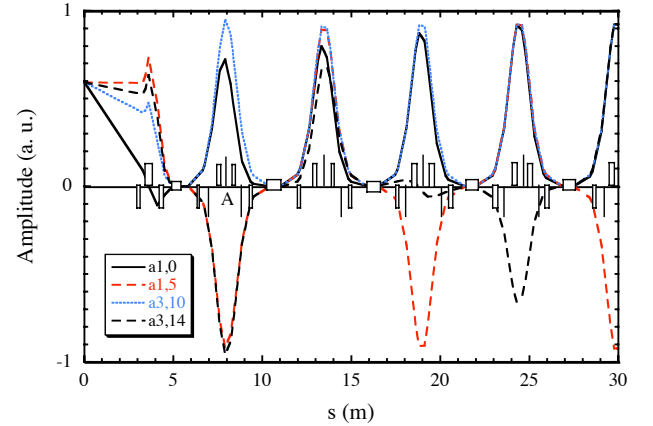


Figure 3: Position dependence of functions $a_{1,0}$, $a_{1,5}$, $a_{3,10}$, and $a_{3,14}$.

We examined the effect of changing the sextupole strength at position A on the dynamic aperture. Actually, a sextupole for chromaticity correction (SFA) is already located at position A, so placing an additional defocusing sextupole (SH) at position A means reducing the strength of SFA. When the strength of SH was changed, the strengths of the other sextupoles for chromaticity correction were also changed to maintain zero chromaticity. The improved dynamic aperture is shown in Fig. 4 together with the one before improvement. The maximum dynamic aperture was -6.5 and $+9.0$ mm.

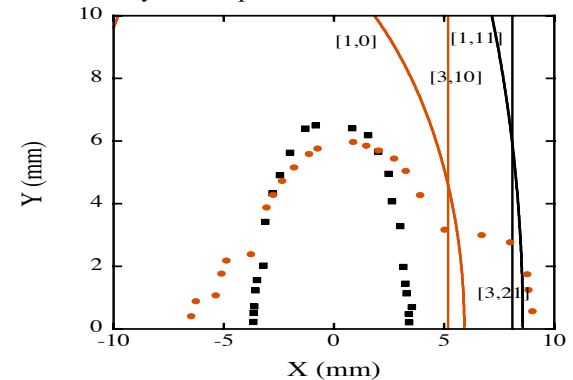


Figure 4: Dynamic aperture before and after improvement.

The dynamic apertures for off momentum particles are shown in Fig. 5. While these apertures are smaller than those of existing storage rings, they are large enough to store an electron beam.

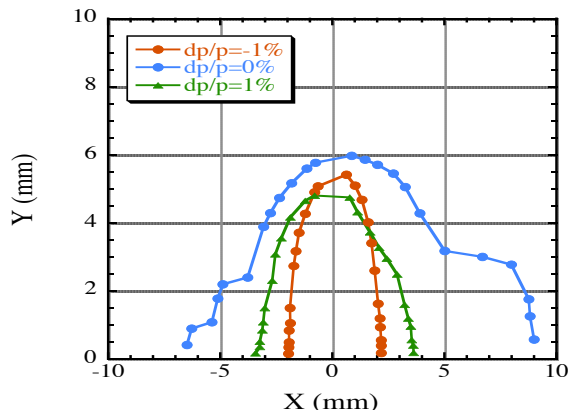


Figure 5: Effect of momentum deviation on dynamic aperture.

EMITTANCE GROWTH AND LIFETIME

Emittance Growth

Emittance growth due to intrabeam scattering was calculated for different coupling constants using the computer code ZAP [5]. The calculated results are shown in Fig. 6, and the beam parameters used in the calculation are listed in Table 2. Betatron and dispersion functions and some parameters listed in Table 1 were also used in the calculation. The minimum bunch current of 0.041 mA corresponds to a beam current of 100 mA if each bucket is filled with a 0.041-mA bunch.

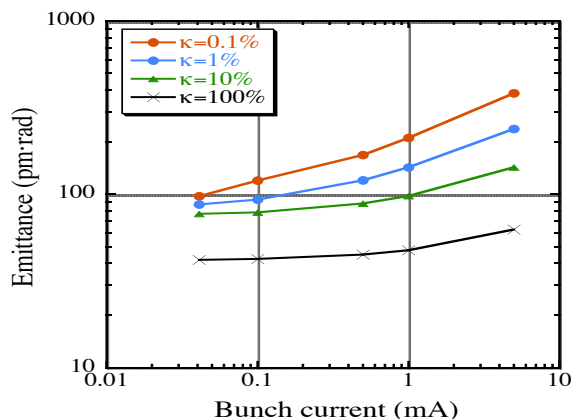


Figure 6: Emittance growth due to intrabeam scattering.

Table 2: Beam parameters used in calculation of intrabeam scattering and Touschek lifetime.

Parameters	Symbol	Value
Bunch length	σ_ℓ	1.62 mm
Damping time	τ_x	12.5 ms
RF frequency	f_{rf}	508.6 MHz
RF voltage	V_{rf}	7 MV
Energy loss	U_0	4.58 MeV/turn

The absolute emittance value for a 0.1-mA bunch current with 0.1% coupling was 112 pm-rad. It decreased to 42 pm-rad with 100% coupling. These results show that the emittance can be kept small while using a realistic beam current if the coupling constant is controlled.

Touschek Lifetime

As shown in Fig. 5, the dynamic aperture for off momentum particles is very small, which shortens the Touschek lifetime. A short lifetime is no longer considered a serious problem due to the potential use of the top-up operation. However, a lifetime that is too short and cannot keep a constant stored current even with the top-up operation is still a problem. We thus estimated the Touschek lifetime using the computer code ZAP [5].

The Touschek lifetime was 0.08 hours for a 0.1-mA bunch current and 0.1% coupling; it was 1.3 hours with 100% coupling. The lifetime with 0.1% coupling may be too short to keep a constant current, while that with 100% coupling should be enough to keep a constant current if the top-up operation is used.

SUMMARY

We designed a very low emittance storage ring for use as a next-generation synchrotron radiation source. It has a 1436-m circumference, an electron beam energy of 6 GeV, and a natural emittance of 83 pm-rad. The circumference is equal to that of SPring-8 storage ring and the cell length is two times that, which enables the replacement of the existing storage ring with this new one in the SPring-8 tunnel and the use of photon beam-lines without constructing new ones.

The horizontal dynamic aperture was -3.7 and $+3.4$ mm at the center of the straight sections. It was increased to -6.5 and $+9.0$ mm by changing the strength of the focusing sextupoles for chromaticity correction at the ends of each cell.

Emittance growth due to intrabeam scattering and the Touschek lifetime were estimated. The emittance was 112 pm-rad and the Touschek lifetime was 0.08 hours for a 0.1-mA bunch current with 0.1% coupling. When the coupling was increased to 100%, they were 42 pm-rad and 1.3 hours.

These results indicate that a storage ring with picometer order emittance is possible with realistic parameters and is a promising candidate for a fourth-generation light source. These results can be easily applied to the combined function dipole magnet case. We are now studying it to obtain a lower emittance ring.

REFERENCES

- [1] L. Emery et al., PAC, New York, 1999, p.200.
- [2] H. Tanaka et al., EPAC'04, Lucerne, 2004, p.222.
- [3] J. Schimizu et al., The 13th Symposium on Accel. Sci. and Tech., Osaka, 2001, p.80.
- [4] R. Nagaoka et al., NIM A 302 (1991) 9.
- [5] M. Zisman et al., LBL Report No. LBL-21270.