ULTRA-LOW EMITTANCE LIGHT SOURCE STORAGE RING CONSISTING OF 5-BEND ACHROMAT CELLS WITH FOUR LONG STRAIGHT SECTIONS

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Abstract

A design study of an ultra-low emittance storage ring for a future SPring-8 storage ring has been done. The circumference and the number of the straight sections are the same as those in the current SPring-8 storage ring, but the energy has been decreased to 6 GeV. The storage ring consists of 44 5-bend achromat cells and four long straight section cells. The natural emittance is 104 pm and was reduced to 52 pm by both damping wigglers and undulators. The horizontal dynamic aperture is +2.7/-2 mm at the centre of each straight section. Detuned lattices with larger dynamic apertures were designed for use in the commissioning. A maximum brightness of 4×10^{22} photons/s/mm^2/mrad^2 in 0.1% BW at around 10 keV is obtained with a 200 mA beam current when all wigglers and undulators are working.

INTRODUCTION

In our previous work, we designed an ultra-low emittance storage ring consisting of 60-m long 10-bend achromat cells and were able to demonstrate that a storage ring with picometer-order emittance is possible within realistic parameters [1]. Since then, we have been carrying out design studies to transform the present SPring-8 storage ring into an ultra-low emittance storage ring.

The original SPring-8 storage ring consists of 44 double-bend achromat (DBA) cells and four long straight section (LSS) cells. Each cell is 30 m in length. At first, we applied ten-bend achromat cells to the SPring-8 storage ring but it does not have LSS, whereas the SPring-8 storage ring does [2]. The photon beam line positions would deviate from those of the existing one. To overcome this problem, we studied a storage ring that had four LSSs [3]. However, this storage ring had only half as many photon beam lines as the original one. In order to increase the number of photon beam lines, we created a short straight section in each cell by removing the sextupole magnets and rearranging the quadrupole magnets located at the centre of the cell [4]. In our current study, we abandoned the 60-meter-long 10-bend achromat cells but employed 30-meter-long 5-bend achromat cells. The number of photon beam lines and the beam line position are now the same as those of the current SPring-8 storage ring.

LATTICE

The storage ring consists of 44 5-bend achromat cells and four LSS cells. The magnet lattice structure of the LSS cell is the same as a regular cell lattice except that the bending magnets are removed. The symmetry of the storage ring is four but the symmetry of the optical function and sextupole distribution is 48, which enables us to avoid reducing the dynamic aperture.

The main parameters are shown in Table 1 and the betatron and dispersion functions are shown in Fig. 1. The horizontal betatron function at the straight sections is set to large by taking the injection into account, though we retain the option of choosing a smaller value to increase the photon beam brightness.

Table 1: Main Parameters of Storage Ring

Parameters	Symbol	Value
Energy	E	6 GeV
Circumference	L	1436 m
Natural emittance	ε_{x0}	104 pm·rad
With damping wiggler	ε_{xw}	52 pm·rad
Number of cells	N_c	
5-bend/LSS		44/4
Horizontal tune	ν_x	115.21
Vertical tune	ν_y	42.72
Horizontal beta at ID	β_x	12.7 m
Vertical beta at ID	β_y	1.8 m
Horizontal chromaticity	ξ_x	-561
Vertical chromaticity	ξ_y	-112
Momentum compaction	α	1.8×10^{-5}
Energy spread	σ_E/E	1.03×10^{-3}
Bunch length	σ_ℓ	1.12 mm
Damping time	τ_x	12.5 ms
RF frequency	f_{rf}	508.6 MHz
RF voltage	V_{rf}	13 MV
Energy loss	U_0	4.6 MeV/turn
+undulator+wiggler	U	9.3 MeV/turn

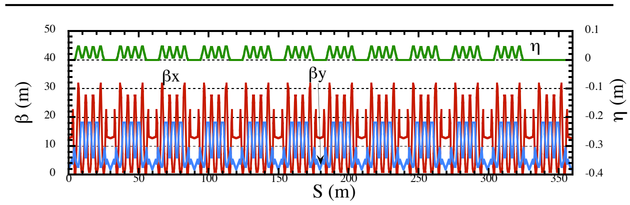

Figure 1: Optics functions in one-quarter of the storage ring.

DYNAMIC APERTURE

The dynamic aperture, which we obtained by particle tracking, is shown in Fig. 2. It is not so large that a new injection method should be studied, but is large enough to store the electron beam.

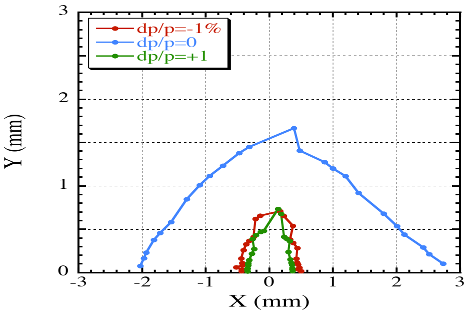

Figure 2: Dynamic aperture at the centre of a straight section.

LONGITUDINAL STABILITY

Since the momentum compaction factor of an ultra-low emittance storage ring is very small, the RF bucket may be largely deviated from the standard one. We calculated the longitudinal phase space to determine whether or not the stability region was large enough to inject and store the electron beam. In the calculation, we assumed a 13 MV RF voltage and 9.3 MeV energy loss including the radiation loss from the bending magnets, undulator, and damping wiggler. The momentum compaction factors from α_0 to α_4 obtained by CETRA [5] were used for the calculation the results of which are shown in Fig. 3. The RF bucket is slightly distorted but the stable region is large enough to inject and store the beam.

Table 2: Parameters used to Calculate the Longitudinal Phase Space

RF voltage	Vrf	13 MV
Energy loss	U	9.3 MeV
Momentum compaction	α_0	1.771×10^{-5}
	α_1	1.313×10^{-4}
	α_2	4.173×10^{-4}
	α_3	7.062×10^{-4}
	α_4	-5.711×10^{-3}

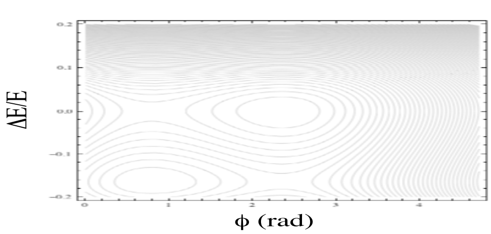

Figure 3: Longitudinal phase space.

DETUNED LATTICE

The dynamic aperture of the storage ring is so small and the sensitivity to errors so high that it might be difficult to start the commissioning with this final lattice. We therefore need to prepare a more relaxed lattice with a larger dynamic aperture and lower sensitivity to errors. The commissioning will be done with this detuned lattice, which enables us to obtain many correction values, such as the steering magnet strength for closed orbit distortion correction. If these correction values are applied to the final lattice, the commissioning process will go much smoother than if the final lattice is used directly with no detuning.

The relation between the phase advance ν_{xtme} normalized by 2π and emittance is shown in Fig. 4 for a theoretical minimum emittance lattice (TME). As the strength of the quadrupole magnets increase, the phase advance also increases and the emittance decreases. A minimum emittance of around 0.47 is obtained in this case though generally the minimum depends on the bending magnet strength. A phase advance of 0.46 was chosen for the original lattice. We designed two detuned lattices, normalized phase advances of which are 0.45 and 0.41, respectively. The optics functions of the detuned lattices are shown in Fig. 5 together with that of the original lattice. The natural emittance for the original lattice is 104 pm. As the focusing strength of the quadrupole magnets decreases, the emittance increases: the emittance of the detuned lattice increases. The emittance for ν_{xtme}= 0.45 is 113 pm, and it becomes 181 pm for ν_{xtme}= 0.41. As the focusing strength of the quadrupole magnets decreases, the dynamic aperture increases, as shown in Fig. 6. For the 181-pm lattice, the horizontal aperture becomes about two times larger than the original lattice. Though the individual aperture size depends on the optimization and ring parameters, this tendency is general for all detuned lattices.

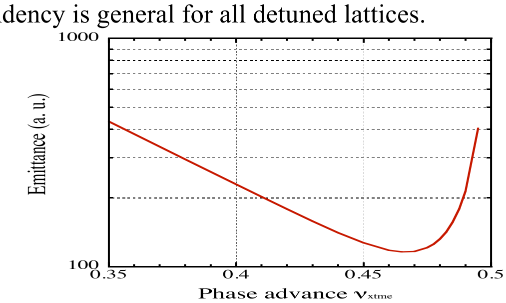

Figure 4: Relation between the phase advance and the emittance for a TME lattice.

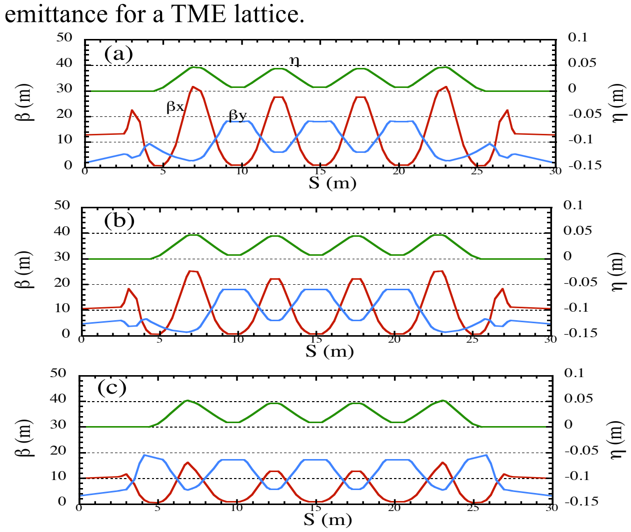

Figure 5: Optics functions in a 5-bend achromat cell for the original lattice (a), and the detuned lattices (b) (c).

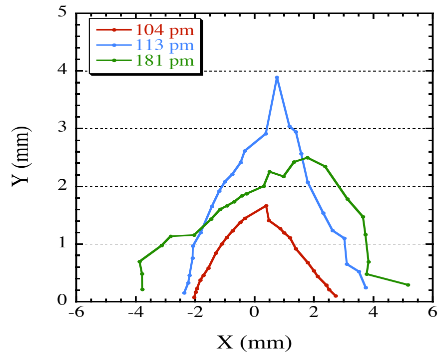

Figure 6: Dynamic apertures of original and detuned lattices.

BRIGHTNESS

There are 44 normal length (5 meters) straight sections (NSSs) and four LSSs in the ring. Four NSSs are used for injection and RF acceleration and the remaining 40 are used for the placement of the undulators. Damping wigglers or undulators are placed in the four LSSs.

We assumed 1.8-cm period and K = 1.34 undulators and 5-cm period and 1.5 T maximum field strength wigglers. The length of the undulators placed in the 5-m-long straight sections is 4.5 m. The total length of the undulators or wigglers placed in each LSS is 10.1 m.

Both the emittance and the energy spread are changed due to the radiation of the undulators and wigglers. We calculated the emittance reduction and energy spread change for the two cases: (1) Every straight section is filled with undulators except for one injection, and three RF sections, and (2) Damping wigglers are placed in the LSSs and undulators fill the NSSs. In case (1), the total undulator lengths in the NSSs and LSSs are 180 m (4.5 m × 40 sections) and 40.4 m (10.1 m × 4 sections). In case (2), the total undulator length in the NSSs is the same as that for the first case and the total wiggler length in the LSSs is 40.4 m.

The brightness was calculated for these three cases using SPECTRA [6] with an undulator period of 1.8 cm, undulator parameter of 1.34, undulator length of 4.5m, beam current of 200 mA, and beam coupling of 0.2 %. The calculation results are shown in Fig. 7. The maximum brightness is about 4×10^{22} photons/s/mm^2/mrad^2 in 0.1 % BW around 10 keV. In this calculation, emittance growth was not taken into account. The bunch must be lengthened to avoid emittance growth and brightness deterioration. The emittance reduction, energy spread, and brightness are summarized in Table 3.

Table 3: Emittance, Energy Spread and Brightness

	ε(pm)	s_E/E	B(ph/s/mm^2/mrad^2/0.1 %BW)
natural	104	1.03×10^{-3}	2.5×10^{22}
undulator	61	1.00×10^{-3}	3.6×10^{22}
wiggler+ undulator	52	1.07×10^{-3}	3.8×10^{22}

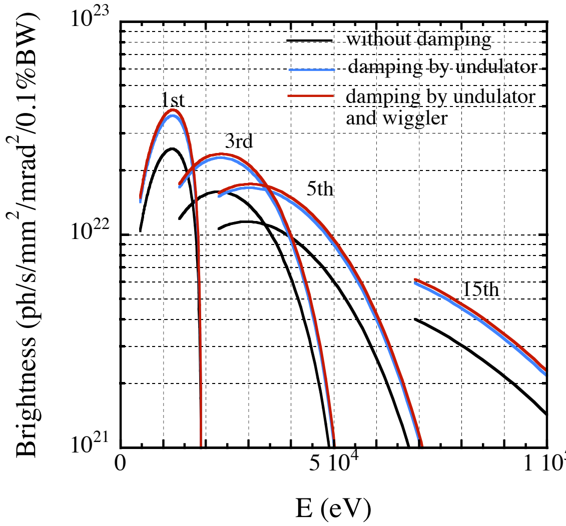

Figure 7: Brightness for a 4.5-m undulator without damping (black), damping by undulators (blue), and damping by wigglers and undulators (red).

SUMMARY

A design study of an ultra-low emittance storage ring for the future SPring-8 storage ring has been done. The storage ring consists of 44 5-bend achromat cells and four long straight sections. The natural emittance is 104 pm and is reduced to 52 pm by both damping wigglers and undulators. The maximum brightness is 4×10^{22} photons/s/mm^2/mrad^2 in 0.1% BW around 10 keV and with a 200 mA beam current.

The horizontal dynamic aperture is so small that we designed detuned lattices that have larger dynamic apertures and lower sensitivity to errors. The dynamic aperture for the detuned lattice with an emittance of 181 pm becomes about two times larger than the original lattice. These detuned lattices are useful in the early stages of commissioning.

The momentum compaction factor is so small that we investigated the longitudinal phase space. The separatrix was large enough to inject and store the electron beam.

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