PROGRESS TOWARD BRIGHTNESS IMPROVEMENTS AT THE SPring-8 STORAGE RING

M. Takao, M. Masaki, S. Matsui, T. Ohshima, K. Soutome, S. Takano, H. Tanaka
SPring-8, 1-1-1 Kouto, Mikazuki, Sayo-gun, Hyogo 679-5198, JAPAN

Abstract

We report on recent and planned brightness improvements at the SPring-8 storage ring with focusing on the optics improvements such as the emittance reduction by non-zero dispersion in the straight sections. The top-up operation is planned to be in use for the purpose of curing reduction of the average brightness in a short beam lifetime operation, which is also reported.

INTRODUCTION

The SPring-8 storage ring is a third generation light source facility and various efforts have been made to provide highly brilliant x-ray beams to users since the beginning of the commissioning, March 1997. The focusing magnets were aligned with very high precision by use of the two-stage alignment method [1] to reduce error fields. This precise alignment and the proper closed orbit correction [2] achieved a very small betatron coupling ratio even without skew quadrupole correction [3, 4]. At the storage ring with such a small coupling, the effect of the vertical dispersion on the vertical beam size is not negligible. At the SPring-8 storage ring the vertical dispersion is corrected by generating counters induced from the horizontal dispersion with skew quadrupole magnets.

The optics of the storage ring has also been optimized for higher brightness. The original optics was the hybrid one which had high and low values of the horizontal betatron function alternately in the straight sections. The hybrid optics was adopted to reduce the effect on the beam instability due to the installation of RF cavities. For the purpose of improving effectively the brilliance of undulators in the low-beta section, we changed the optics to the one that have the high horizontal betatron function and the low vertical one in all straight sections, which we call the HHLV optics. Recently we further changed to a new optics with a smaller natural emittance by introducing non-zero dispersion in the straight sections [5]. This method of emittance reduction is effective for the case where undulators with a moderate field strength are used. This optics is called a low-emittance optics.

As another way of increasing the brightness we changed the lattice structure of the ring to realize magnet-free long straight sections for installation of a very long undulator. The initial lattice structure of the storage ring was based on the double-bend achromat with 48 unit cells, which is called a 'Phase-I lattice'. There were four long straight cells without bending magnets. In summer shutdown of 2000, four magnet free long straight sections, which were about 27 m long, were realized by removing quadrupole and sextupole magnets in the straight cells and rearranging the sextet quadrupoles at both ends of a long straight cell [6]. This new lattice structure is called a 'Phase-II lattice'. At present the 25-m-long undulator is installed at one of the four long straight sections, which provides more brilliant light to users than normal length 4.5-m-long undulators.

Table 1: Parameters of the SPring-8 storage ring.

Energy [GeV]		8
Current [mA]		100
Horizontal tune		40.15
Vertical tune		18.35
Emittance [nmrad]	(Achromat)	6.6 (ID's open)
		5.3 (ID's close)
	(Low-emit.)	3.4 (ID's open)
		2.9 (ID's close)
Coupling ratio		0.002
Energy Spread		0.0011

The major beam parameters of the SPring-8 storage ring in cases of the achromat and the low-emittance optics are listed in Table 1.

Even at the SPring-8 storage ring with relatively high energy 8 GeV, the reduction in emittance may significantly reduce the beam lifetime due to the Touschek effect. In the single bunch operation of a high peak current per bunch the reduction of the lifetime becomes more conspicuous. To cure the short lifetime in the low emittance operation, we plan to operate the storage ring in top-up injection mode. However, the stored beam oscillation excited by the beam injection disturbs the user experiments and deteriorates the effective brightness. For the purpose of accomplishing the top-up operation free from the disturbance, we provide means to suppress the stored beam oscillation at the beam injection.

The orbit stabilization of an electron beam is also effective for the brightness improvement, so we made efforts to achieve the stability of sub-μm at the SPring-8 storage ring. The details of this topic are found in [7] and will not be discussed in this paper.

OPTICS IMPROVEMENT

Vertical Dispersion Correction

Vertical emittance ϵ_y of a high-energy electron beam in a storage ring is characterized by the radiation excitation and the coupling between the horizontal and vertical betatron oscillations. In a single resonance approximation it is written as

$$\epsilon_y = \frac{\kappa}{1+\kappa}\epsilon_{xr} + \frac{1}{1+\kappa}\epsilon_{yr}, \qquad (1)$$

where $\epsilon_{x(y)r}$ is the horizontal (vertical) emittance excited by the radiation in the non-zero dispersion region, and κ is the coupling ratio of the betatron oscillations. Assuming longitudinal and transverse motions are independent with each other, the vertical beam size is given by

$$\sigma_y(s) = \sqrt{\beta_y(s)\,\epsilon_y + \eta_y^2(s)\,\sigma_\delta^2}, \qquad (2)$$

where $\beta_y(s)$ is the vertical betatron function, $\eta_y(s)$ the vertical dispersion function, and σ_δ the r.m.s. momentum spread. As shown in Table 1 the betatron coupling is sufficiently small and it is hard to perform a coupling correction and to reduce it further. Instead the vertical dispersion has room for improvement. Using 20 skew quadrupole magnets, we have reduced the vertical dispersion from 3.9 mm (r.m.s.) to 1.3 mm (r.m.s.) and this improved the vertical beam size by about 10 %. This was confirmed by the measurement with the visible light interferometer [8].

It is noted that the strengths of the skew quadrupole magnets are determined not to change the resonance condition. Through computer simulation we found that, in order to excite skew quadrupole magnets with keeping the resonance condition, we need to suppress 6 differential and sum linear resonance lines near the operation point [4].

HHLV Optics

The betatron function of the HHLV and hybrid optics in a unit cell are shown in Fig. 1. The horizontal betatron function of HHLV optics takes high value at all straight sections, while that of hybrid optics takes high and low values alternately. Since the horizontal emittance of the electron

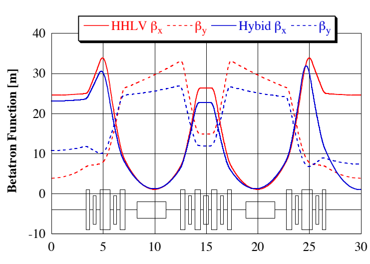

Figure 1: Betatron functions in a unit cell.

beam is relatively large compared to photon beam, the photon flux density of an undulator placed at the low beta section in hybrid optics is increased by using the HHLV optics as shown in Fig. 2.

As a by-product of the optics change the symmetry of the lattice is significantly improved so that the beam lifetime in the HHLV optics becomes much longer compared to the hybrid optics.

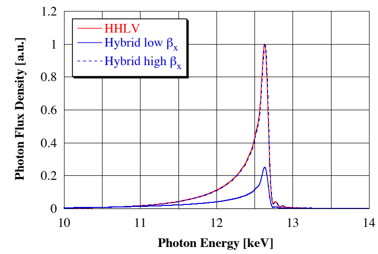

Figure 2: Photon flux densities of a SPring-8 standard undulator observed at a distance of 50 m from the source point.

Emittance Reduction by Non-zero Dispersion in the Straight Sections

The peak of the dispersion function in a bending magnet can be lowered by allowing non-zero dispersion in the straight section. Then the radiation excitation in a bending magnet and hence the emittance are reduced. If the field of an insertion device (ID) placed at a straight section is not so strong, the radiation excitation due to ID is negligible. The dispersion function is optimized so that the effective emittance includind the effect of the energy spread at a straight section for ID takes the minimum value.

Applying this method to the SPring-8 storage ring as shown in Fig. 3, we could reduce the emittance by half. Figure 4 shows observed interference pattens in the horizontal direction by the visible light interferometer, from which the horizontal emittances were estimated to be 3.4 nmrad and 6.6 nmrad for low emittance and achromat optics, respectively. This emittance reduction increases the photon flux density of the photon beam by about 30 % as shown in Fig. 5.

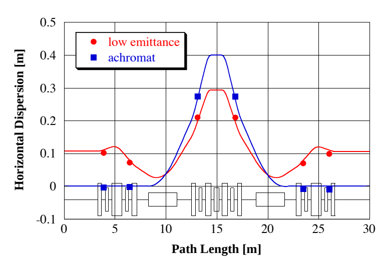

Figure 3: Horizonatal dispersion of the low emittance optics (red circles) and that of the achromat (blue suares) in a unit cell. Solid lines indicate the calculated dispersion.

At present we have a lot of ID's, whose radiation loss contributes to the radiation damping. When the gaps of ID's are closed, the emittance reduction of about 20 % is observed in the achromat optics. Even in the low emittance optics the value of the dispersion in a straight section is well optimized so that the radiation from the ID's does not enhance but reduce the emittance as shown in Table 1.

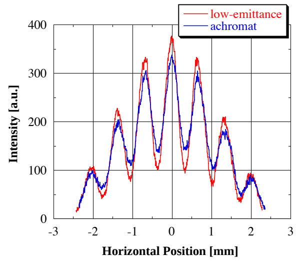

Figure 4: Observed interference patterns by the visible light interferometer. The red (blue) line corresponds to the low-emittance (achromat) optics.

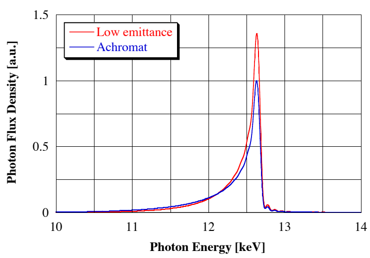

Figure 5: Photon flux densities of the low emittance (solid line) and achromat (dotted line) optics.

TOP-UP OPERATION

Although the electron energy of the SPring-8 storage ring is relatively high, being 8 GeV, the emittance and the coupling ratio are so small that the Touschek effect can not be ignored. This becomes a serious problem especially in several or single bunch operation where the beam density is required to be high. The short beam lifetime spoils the integrated brightness and so we have decide to operate the SPring-8 storage ring in top-up injection mode. The operation with 203 bunches, which is one of the typical filling patterns in user operation, has a beam lifetime of about 20 hours and the beam is currently injected every 12 hours. When we keep the stored current maximum, 100 mA, the integrated brightness can be increased by 25 %. Since last autumn the frequent beam injection whose repetition is every one minute has been carried out several times. During the test the current was kept 100 mA over five hours, and a fluctuation of the current was confined within 0.15 %.

In addition to such enhancement of the integrated brightness, the top-up operation is effective for keeping the heat load of the beamline components constant. This is also useful for increasing the integrated brightness because the thermal transient by the beam injection disturbs user experiments and deteriorates effective integrated brightness. This situation becomes even worse when main beam shutters located in the front-end of beamlines are closed during beam injection.

As another source of deterioration of the integrated brightness there can be an oscillation of a stored electron beam induced by injection bump magnets. At each injection the stored beam is pushed to the injection trajectory by the pulse-bump magnets. Then if the pulse-bump orbit does not close, the stored beam oscillation is excited, which disturbs user experiments and should be suppressed. In the horizontal plane, main sources of the imperfection of the bump orbit are the non-similarity of field patterns of the pulse-bump magnets and the non-linearity of the field induced by sextupole magnets located in pulse bump orbit. The dashed line in Fig. 6 shows the r.m.s. amplitude of the horizontal beam oscillation. The abscissa is the time after firing the bump magnets. Narrow peaks originate in the field pattern non-similarity of bump-magnets and broad ones come from the sextupole non-linear field. We found that the cause of the field pattern non-similarity of the pulse-bump magnets is the Eddy current in the metallic end plates [9]. By replacing them with non-metallic end plates, we could improve the field pattern non-similarity of the pulse bump magnets. As for the sextupole non-linear field we found the condition for the strength of sextupole magnets to excite less oscillation of the stored beam [10]. Applying these to the SPring-8 storage ring, we suppressed the stored beam oscillation to the level shown by the solid curve in Fig. 6. The order of magnitude of the vertical oscillation was 0.1 mm. By tilting some of the pulse-magnets and installing a corrector pulse-magnet, we reduced it to one third of the vertical beam size. At present the beam injection scarcely interrupts user experiments, and it is expected that when top-up injection is applied to user operation the x-ray beams are provided without any dead time.

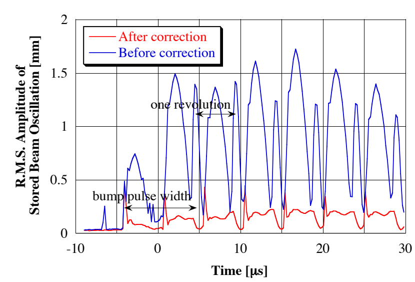

Figure 6: Amplitude of the horizontal stored beam oscillation by pulse bump orbit (r.m.s.). Time 0 corresponds to the timing of a peak of the bump orbit.

REFERENCES

[1] H. Tanaka, et al., N.I.M. **A313** (1992), 529.

[2] K. Soutome, et al., N.I.M. **A459** (2001), 66.

[3] M. Takao, et al., in Proc. of the 1999 PAC (1999), 2349.

[4] H. Tanaka, et al., in Proc. of the 2000 EPAC (2000), 1575.

[5] L. Farvacque, et al., in Proc. of the 1994 EPAC (1994), 612; H. Tanaka and A. Ando, N.I.M. **A369** (1996), 312.

[6] H. Tanaka, et al., N.I.M. **A486** (2002), 521.

[7] http://www.spring8.or.jp/e/conference/iwbs2002/.

[8] M. Masaki and S. Takano, J. Synch. Rad. **10** (2003), 295.

[9] T. Ohshima, in Proc. of the 14th Symposium on Accelerator Science and Technology (2003), 223.

[10] H. Tanaka, et al., to be published.