RECENT PROGRESS OF THE SPring-8 FACILITY

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Abstract

Since October 1997, the SPring-8 facility has been operated well and provided high quality photon beams for users. Over this period, various kinds of improvements have been carried out to achieve brilliant and stable photon beams and to make the most of 8-GeV potentiality. At the same time R&D has continued for future radiation sources. In these activities, the largest achievement has been the construction of magnet-free long straight sections (LSS's). Owing to a sufficient preparatory study, the LSS's were successfully commissioned and user operation was re-started in October 2000. This paper presents a recent progress overview of the SPring-8 facility.

1 SPring-8 ACCELERATOR COMPLEX

The SPring-8 facility is a highly brilliant X-ray source providing photon beams having an energy range of from 0.2 to several hundreds keV. It is composed of a 1-GeV injector linac, an 8-GeV booster synchrotron and an 8-GeV storage ring [1]. The construction of the SPring-8 facility started in 1990 and the beam commissioning of the storage ring started in the middle of March 1997. By way of the smooth beam commissioning the user operation started in October 1997. Since completion of the commissioning, the SPring-8 facility has been operated well and the total user time has reached more than 12800 hours, 70% of the total beam time. Over this period, the beam time per year is smoothly growing from 1271 hours in 1997 to 4973 hours in 2000. Before 2001 the storage ring was usually operated with a cycle of three weeks. To increase the user time, operation with a cycle of four weeks was recently introduced [2].

1.1 Injector Linac

The 1-GeV linac consists of a thermonic gun, a bunching system, twenty-five accelerating sections and an energy compression system (ECS) [3,4], which was recently installed to stabilize the electron beam energy. The thirteen 80-MW klystrons (TOSHIBA E3712) feed a radio frequency (rf) power of 2856MHz to the accelerating structures. The linac can accelerate short (1ns) and long (40ns) electron beam pulse widths mainly depending on the storage ring operation requirement. Since September 1998, the linac has been supplying short pulse beams to the synchrotron radiation source "NewSUBARU" [5]. The destination can be changed from the booster synchrotron to NewSUBARU and vice versa by using a switching dipole DC magnet. The electron gun is usually driven at 1pps, but the repetition rate can be increased up to 60pps in response to the operational demands. The main beam parameters are listed in Table 1 [6].

Table 1 Main parameters of the beam accelerated by the linac with ECS turn on.

	NewSUBARU	Synchrotron	
Pulse Width [ns]	1	1	40
Repetition [pps]	1	1	1
Current [A]	0.2	2	0.35
$\delta E/E$ (full width)	---	---	0.014
Energy stability (rms)	---	0.0002	---
Normalized Emittance [μmrad]	$<200\pi$	$<160\pi$	$<240\pi$

1.2 Booster Synchrotron

The 8-GeV synchrotron has a circumference of 396m. The synchrotron consists of 40 FODO cells and two dispersion-free straight sections about 30m long [7]. Each straight section has two dispersion-suppression cells at both ends. One straight section is used for both the rf station and beam injection from the linac, and the other for the beam ejection to the storage ring. The synchrotron accelerates the injected beam from 1 to 8GeV at a cycle of 1Hz with eight sets of five-cell rf cavities driven by 508.58-MHz rf. A single-bunch beam is presently formed in the synchrotron by applying a radio frequency knockout (rf-KO) system to the injected beam of a 1-nsec pulse width during the flat-bottom of 250ms [8]. In the SPring-8 storage ring, strong radiation damping prevents scattered electrons from diffusing to the back rf buckets and hence a good purity is routinely obtained in the single-bunch operation. The main parameters are listed in Table 2 [9].

Table 2 Main parameters of the synchrotron at 8GeV

	Design
Tune (ν_x,ν_y)	(11.73, 8.78)
Horizontal Emittance [nmrad]	230
Bunch Length (rms) [ps]	61
Momentum Spread	0.00126
Momentum Compaction Factor	0.01

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1.3 Storage Ring

The storage ring has a circumference of 1436m, and before the installation of the LSS's it consisted of 48 Chasman-Green (CG) cells. Four of them were "straight cells" in each of which two bending magnets are removed from a CG cell to maintain the symmetry of the optics. Besides these straight cells, which were converted to the LSS's, the storage ring has 40 dispersion-free straight sections 6.65m long. One of them is used for beam injection and four are used for rf stations, each consisting of eight single-cell rf cavities driven by 508.58-MHz rf [10]. The remained thirty-four sections are for the installation of insertion devices (ID's). At present, the number of installed ID's has reached 21 including the one long undulator. Users can change ID parameters, i.e. a gap and a phase independently during user operation.

2 IMPROVEMENTS AND R&D ACTIVITIES AT SPring-8

The improvement of the accelerator performance and R&D on accelerator components have been carried out based on following three courses:

- Generation of brilliant and stable photon beams.
- R&D for future radiation sources.
- Best use of the 8-GeV potentiality.

2.1 Generation of Brilliant and Stable Photon Beams

When the storage ring is operated with several-bunch filling, the peak current becomes high and the beam lifetime markedly decreases due to the Touschek effect even at an 8-GeV beam-energy. To suppress the reduction of the time-averaged brilliance "top-up operation" has been investigated since 1999. The injection magnets of the storage ring were modified to minimize the perturbation to the stored beam in the summer shutdown period of 2001. At the same time, the mechanism of the injected beam loss has been studied. The present results show that a part of injected electrons is lost at the in-vacuum ID's with a gap of 8mm under high chromaticity. The results also suggested that this loss relates to a mismatch in the longitudinal phase space. Besides the optimization of the storage ring lattice parameters, we have also been investigating the possibility reducing the equilibrium bunch length in the booster synchrotron. To simulate the top-up operation we have also been developing a 6-by-6 tracking simulator that includes synchrotron radiation, full kinematic terms and short-range wake-force.

The reduction of transverse emittance directly increases the photon beam brilliance. Considering this, the vertical emittance has been kept at around several pmrad by fine orbit correction [11] and by vertical dispersion suppression with skew quadrupole magnets. Figure 1(A) shows the dependence of the inverse of the Touschek lifetime on the vertical excitation parameter measured by systematically changing the vertical dispersion [12]. The excitation parameter stands for the averaged vertical size variation in changing the vertical dispersion. From these data the vertical emittance coming from the H-V coupling was estimated to be 4.2pmrad before the installation of the LSS's. Effort to reduce the vertical emittance is still ongoing. On the other hand, the reduction of the horizontal emittance was also investigated by controlling the damping partition number. It is clear that the horizontal effective excitation of a betatron oscillation decreases as the beam energy reduces from the design value. As shown in Fig. 1(B) the horizontal emittance can be decreased down to 2nmrad, about one third of the original value [13].

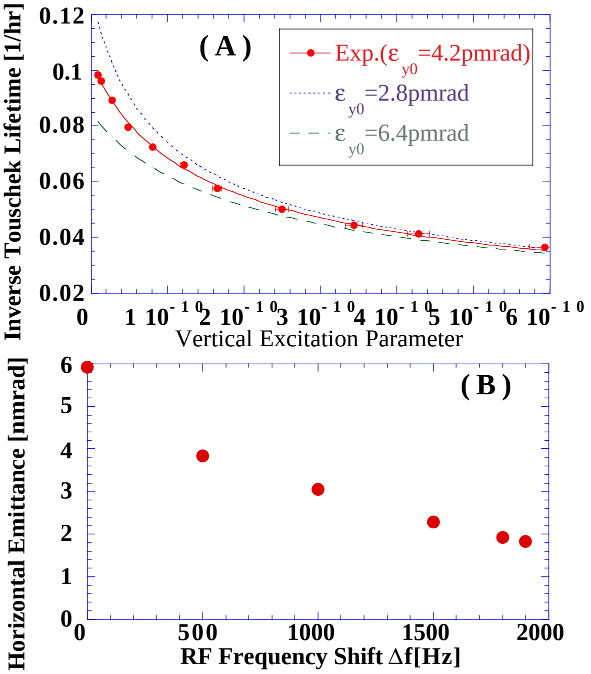

Figure 1: The upper figure (A) shows the inverse of the Touschek lifetime versus the vertical excitation. The lower figure (B) shows the horizontal emittance versus the rf frequency shift. The data in both figures were measured before the installation of the LSS's.

To suppress the beam instability the storage ring is presently operated under high chromaticity [14]. This high chromaticity has been observed to cause some serious problems: the reduction of the beam lifetime, the H-V oscillation mixing of the injected beam and so on. Toward low chromaticity operation, we are planning to install a feedback system for coherent instability suppression in the storage ring.

The beam orbit stability is also crucial for the generation of brilliant and stable photon beams for a synchrotron radiation source. In this field, various improvements were carried out. The most significant progress has been the improved current stabilizing circuits in the quadrupole magnet power supplies, which markedly reduce the current ripples and drifts [15]. Figure 2 shows the difference between the beam spectrum before and after the improvements. Second, the coherent synchrotron oscillations were suppressed by the frequency modulation of the reference rf generator. The frequency is now modulated by a feedback loop to cancel out the phase difference between the reference and beam signals [16]. Third, a new signal processing system for a beam position monitor (BPM) was developed to measure fast orbit motions. The new BPM system can cover from DC to a few tens kHz. We can use the four systems to make a synchronaized measurement of the beam motion at the four points along the ring. By these measurements, the error field of each ID was corrected to make ID's more transparent against orbit distortions. The data shown in Fig. 2 were measured by this new system.

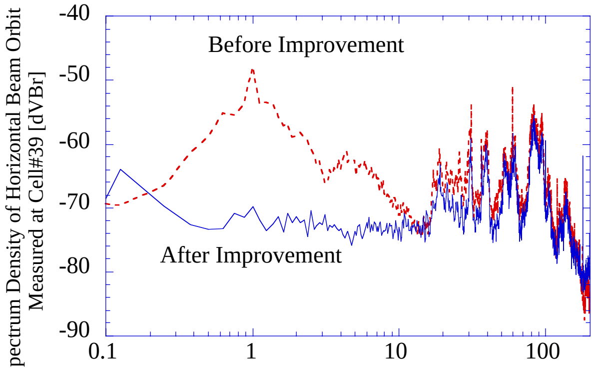

Figure 2: Power spectrum of the horizontal orbit before and after the improvements.

2.2 R&D on Future Radiation Sources

Spatially coherent X-ray generation is one of the challenging issues in accelerator science. A high quality electron beam with short bunch length and low emittance would be indispensable to realize such X-ray radiation. Development of a photocathode rf gun has been carried out because the gun performance, i.e. initial beam quality is essential for any beam application including linac-driven SASE. The data shown in Table 3 were achieved by a test bench [17]. To effectively improve the design of the rf gun, a three-dimensional simulation code was also developed [18]. This code explains well the following experimental results.

Table 3 Performance of rf gun test bench

Normalized Emittance [μmrad]	6π
Charge per Pulse [nC]	0.3
Beam Energy [MeV]	3.1
Laser Pulse Width [ps]	20
Beam Pulse Width (calculation) [ps]	7

As another possibility, ring-based SASE was investigated on the premise that LSS's are installed in the storage ring [19]. In this case, from the viewpoint of an FEL gain and electron beam quality, low energy operation is needed. The target beam energy is presently estimated to be 3 ~ 4GeV. The preparation for the low energy operation is now being made. In parallel with the preparation, the beam diagnostic's beamline is under construction to measure rather small beam sizes of a few microns, short bunch length and so on [20].

To generate spatially coherent X-rays the transverse phase volume of an electron beam should be comparable to that of an emitted photon with the target energy. This means that the transverse emittance of the electron beam should be smaller than that for usual undulator radiation. Accordingly, the beam trajectory or orbit needs to be remarkably stabilized. In January 2001, project was therefore started on beam orbit stabilization to achieve orbit stability of sub-micron order in linear and circular accelerators. At present, we have been particularly investigating what degree fluctuations of environmental and machine parameters affect the orbit stability.

2.3 Best Use of 8-GeV Potentiality

The circumference of the storage ring became large to satisfy a low emittance requirement at the high beam energy of 8GeV. In fact, this large circumference is a great advantage for experiments using the time structure of the pulsed photon beams. Moreover, owing to the precise timing system [21], the users can easily select the time interval of the pulsed photon beam from 2ns to 4.8μs by a 2-ns step and can also select the current distribution according to users' requirements. To make the best use of this capability it is important to maintain the reproducibility and uniformity of the beam pulse injected into the storage ring. However, the fluctuation of the beam energy and energy spread at the linac caused the current variation of the injected beam pulse.

To solve this problem, an ECS was constructed at the end of the linac to reduce the energy spread of the accelerated beam and to stabilize the beam centre energy. Experimental data showed that the ECS has almost the same performance as the simulated one. For example, in the case of a 40-ns beam pulse injection, the ECS reduces the energy spread from 3.5% to 1.4% in full width. Consequently, the stored current in the synchrotron was increased by seven times [4,6] without exceeding the beam loss limitation for safe operation. Furthermore, since the ECS can compensate for energy-shifts due to a beam loading effect, the filling pattern in the storage ring is now precisely controllable by adjusting the electron gun emission. The ECS is routinely used for the scheduled beam injection in user operation.

It is also crucial to improve the purity of the single-bunch filling. To this end a new high-power amplifier replaced the old one for the kicker magnet in the rf-KO system. As a result of tuning the machine parameters of the synchrotron, impurity of a few parts per billion was obtained. As a different approach, the combination of a fast beam chopper [22] with a shorter linac pulse width has been investigated to reduce the dark current emitted by the gun and to suppress the fluctuation of single-bunch current. To realize this idea, it is essential to control the phase difference between the linac and synchrotron rf's. Without fixing the phase difference the fluctuation of the single-bunch current occurs shot by shot after the rf-KO procedure. A part of the timing system was thus modified to synchronize the 2856-MHz to 508.58-MHz rf's in only a short period during beam emission and acceleration in the linac [23]. Single-bunch formation testing is scheduled to start in the autumn of 2001 by using a shorter linac pulse width of 250ps [24].

The stored beams of 8GeV have the potentiality of generating high energy X-rays with an existing high magnetic field. Those generated photons having energies higher than 1MeV are converted to positrons with very low energies through pair-creation by a certain probability. For the production of an intense positron beam with extremely low energies, a prototype super conducting wiggler (SCW) was recently fabricated in collaboration with Budker INP. A maximum field strength of 10.3T [25] was achieved. To install such a high-field SCW in the storage ring, its stability and effects on the lattice parameters must be checked carefully in addition to heat-load problems. We are now planning to study these problems by using the prototype wiggler and to check the feasibility of installation.

The stored beams of 8GeV can also generate gamma-rays of high energy through collision with laser beams, i.e., a Compton back scattering process. For example, when the wavelength of laser beams is set to 118.8μm, i.e. the far infrared (FIR) energy-region, the Compton edge becomes lower than 10.2MeV and colliding electrons still remain in the inside of the momentum acceptance of the ring. This suggests that the intense gamma-rays are obtained without serious degradation in the beam performance, especially the beam lifetime. To achieve the above scenario an optically pumped FIR laser has been developed [26].

3 RECENT TOPIC: CONSTRUCTION OF FOUR LSS'S

From October 1997 to July 1999 the storage ring had been operated with hybrid optics. In this optics a horizontal betatron function takes a large value (high-beta) and a small value (low-beta) alternately in magnet-free straight sections for ID's. In September 1999 the hybrid optics was changed to HHLV optics (optics with High Horizontal and Low Vertical betatron functions in all straight sections) to meet the requirements of using undulators in the low-beta sections of the hybrid optics. In the HHLV optics, a vertical betatron function is also reduced to a small value in order to increase the brilliance of photon beams at the source point and to suppress the de-magnetization of undulators due to scattered electrons. Until this stage, the ring holds a highly periodic structure called "Phase-1 lattice". In the summer shutdown period of 2000, the magnet arrangement of the long straight sections was modified and four LSS's 27m long were constructed. New lattice structure is called "Phase-2 lattice". Figure 3 shows typical optical functions for the Phase-1 and Phase-2 lattice structures.

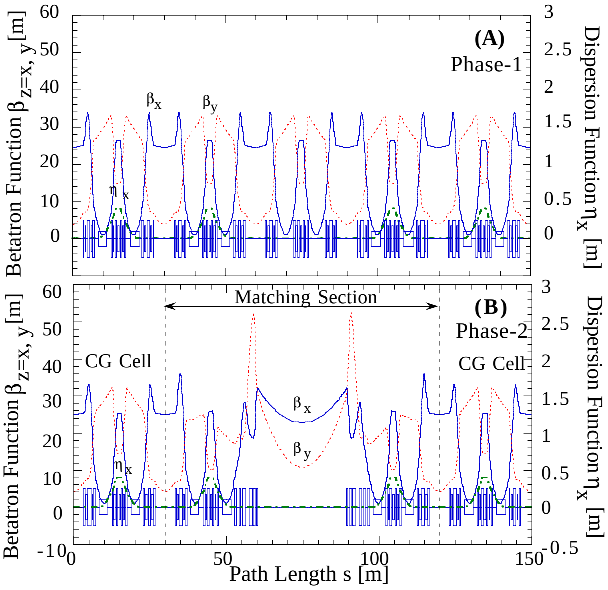

Figure 3: Typical optics of Pase-1 (A) and Phase-2 (B).

The installation of the LSS's apparently breaks high symmetry of the ring optics. It was easily predicted that this symmetry-break markedly deteriorates the stability of electron beams. To overcome this, a concept of "quasi-transparent matching of sextupole fields (QTMS)" [27] was developed. The QTMS concept simultaneously manages both the symmetry restoration of sextupole fields and the local chromaticity correction in a proper way. To apply the QTMS concept to the phase-2 lattice, we adopted the matching section about 90m long, which comprises of one LSS and neighboring two CG cells as shown in Fig.3. Over the matching section, horizontal and vertical betatron phase advances are adjusted respectively to 4π and 2π to make the LSS transparent for on-momentum electrons. Owing to the lattice design based on this concept, we could achieve the performance which nearly equals to that of the previous lattice without the LSS's (Phase-1) in a short period, only 3 weeks. The achieved performance is listed in Table 4. The user operation was re-started in October 2000 as scheduled. In one LSS the very long in-vacuum undulator 25m long was also installed in the same period and it has been routinely used in user operation [28].

Compared with the Phase-1 lattice, the performance of the Phase-2 lattice is worse in the momentum acceptance.

For its improvement, we have been investigating effects of optics-symmetry restoration and suppression of the plural coupling resonance lines nearby the operation point. The necessary error field distribution for this investigation was estimated with a model calibration method based on 4-by-4 formalism, which can treat full transverse oscillation mixing.

Table 4 Achieved performance and machine parameters of the storage ring[*1]

	Phase-1 w/o LSS's	Phase-2
βx/βy at ID center [m]	25/4[*2]	24.4/5.8[*2] 23.4/14.4[*3]
Tune ν_x/ν_y	43.16/21.36	40.15/18.35
Beam Current [mA]		
Single-bunch	16	13
Multi-bunch	100	100
Bunch Length (FWHM) [ps]	32	32
Horizontal Emittance [nmrad]	6.0[*4]	6.3[*4]/7.3[*5]
Vertical Emittance [pmrad]	5.5[*6]/13.6[*5]	14.2[*5]
Operation Chromaticity ξ_x/ξ_y	+7/+4	+7/+6
Momentum Acceptance [%]	2.9	2.1
Beam Lifetime [hr]		
100mA(multi-bunch)	~140	~150
1mA(single-bunch)	25	22
Dispersion Distortion [mm]		
Horizontal (rms)	~4	~4
Vertical (rms)	~1.1	~1.1
Orbit Stability (tune harmonics) [μm]		
Horizontal (rms)	0.7	1.3
Vertical (rms)	0.35	0.35

[*1] Vrf=16MV [*2] normal straight section

[*3] long straight section

[*4] estimated with the beam size measured by a pulsed bump and scraper [29]

[*5] estimated with the beam size measured by a two-dimensional interferometer [30]

[*6] estimated by Touschek lifetime and systematic change of a vertical dispersion [12]

4 SUMMARY

Recent progress at the SPring-8 facility was overviewed. Various improvement activities and R&D have been widely performed at the SPring-8 accelerator complex, and these activities have been well conducted toward three innovative courses. We believe that some of these activities including use of the potentiality of the LSS's will open new possibilities in accelerator science and technology.

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