Chapter 6

Light Sources and X-ray Optics

6.1 Light Sources

In this section, an overview of light sources available in SPring-8 II is presented. Firstly, the basic policy on how to define the specifications of insertion devices (IDs) to be installed in the storage ring is described. Secondly, details of IDs in several typical beamlines are presented together with expected light source performances to compare with the current values. Finally, a couple of technical issues are addressed, which are crucial for the upgrade plan and operation of the new storage ring.

6.1.1 Basic Policy on ID Specification

The insertion device (ID) is one of the most important components in a synchrotron radiation (SR) facility, which actually produces high-quality SR from the electron beam accumulated in the storage ring. The quality of SR is generally characterized by three physical quantities, i.e., the brilliance, flux, and spatial coherence. In order to discuss the comprehensive performance of a SR beamline, however, we need to consider another important characteristics, i.e., the radiation power, which denotes the photon intensity obtained by integrating the photon flux over the entire energy range. In most of the experiments using a monochromatized photon beam, only the photons contained in the bandwidth and angular acceptance of the monochromator are irradiated to the sample. The other photons are absorbed by front-end components and optical elements in the beamline and then turn to heat sources in the respective devices. If the cooling capability of a particular component is not sufficient, the component can be significantly damaged or at least deformed. Such a heat load problem is especially serious for the optical elements such as monochromators and mirrors, because the deformation of these devices results in a fluctuation of the photon beam position at the sample and a variation of the energy resolution, which can lead to a significant reduction in the effective brilliance and flux. In this sense, specifications of IDs should be defined not only to optimize the brilliance and flux but also to reduce the radiation power or heat load, especially on the optical elements.

It is well known that IDs can be classified into two types, i.e,, undulators and wigglers. As discussed in the followings, the undulator is much more advantageous than the wiggler, toward improvement of the brilliance and reduction of the heat load. This is more noticeable in the ultra-low emittance storage ring, which is one of the important keywords for the upgrade plan of SPring-8.

Let us first consider the selection of IDs in terms of the brilliance. Roughly speaking, the brilliance is evaluated by dividing the total flux by the effective optical emittance, i.e., the product of the source size and angular divergence. Because the total flux is simply proportional to the number of ID periods, the total flux from a wiggler is close to that from an undulator having the same number of periods. As long as the SR emitted from a single electron is concerned, the effective optical emittance of undulator radiation (UR) is always equal to the natural optical emittance (emittance of diffraction-limited light) and is independent of the number of periods. On the other hand, the effective optical emittance of wiggler radiation (WR) grows as the number of periods increases, and thus the brilliance of WR is usually a couple of orders of magnitude less than that of UR.

Next let us discuss the issue on how to reduce the heat load. The radiation power can be reduced by intercepting the off-axis photons by the so-called XY slit placed in the front-end section. This scheme, when applied to UR, works well because the angular spread of the photon flux at the fundamental energy (and high-harmonic energies) is much smaller than that of the radiation power, which can be eliminated effectively by the XY slit having an appropriate opening angle, without significantly sacrificing the flux. This is not the case for WR, because the angular profiles of the photon flux and radiation power are close to each other and thus narrowing the slit aperture to reduce the heat load results in the loss of available flux.

It is worth noting that the validity of the above discussions largely depends on the electron beam emittance. If it is much larger than the natural optical emittance, the brilliance does not largely depend on the type of ID any more, and the heat load reduction using the XY slit is not so advantageous because the flux angular profile is broadened by the convolution with the electron beam distribution. This in turn means that the lower the electron beam emittance becomes, the more advantageous the undulator is over the wiggler.

Summarizing the discussions above, undulators are supposed to be the main IDs in SPring-8 II and wigglers are to be selected only when the users request special optical properties that cannot be provided by undulators, such as a white spectrum or broad spatial profile.

In the following sections, specifications of IDs to be installed in several typical beamlines are presented together with the calculation results of expected light source performances.

6.1.2 Hard X-ray Beamline

Firstly, specifications of IDs for hard X-ray beamlines (HXBLs) are described. In terms of the available brilliance and flux, the magnetic period should be as short as possible. In SPring-8, in-vacuum undulators (IVUs) have been aggressively adopted in pursuit of shortening the magnetic period. In SPring-8 II, the cryogenic undulator (hereinafter cryo-undulator), which is an extension of IVU, is supposed to be the standard ID for HXBL toward further shortening of the magnetic period. In order to cover the photon energy region down to 5 keV, which is similar to that of the existing SPring-8 standard beamline, the possible shortest magnetic period is found to be 14.4 mm with the minimum gap being assumed to be 2 mm (see Section 5.2.1).

If the energy region can be confined to a more narrow one, the magnetic period can be shorter to improve the brilliance. This concept has been already applied to several beamlines in SPring-8. For example in BL35XU, an IVU with a magnetic period of 20 mm, which is the shortest one in SPring-8, is installed, and covers the photon energy region from 14.4 to 26 keV. If we would apply the same concept to SPring-8 II, the magnetic period could be shortened down to 10.2 mm. As shown later, this would result in an enhancement of the brilliance three times and flux twice. If a more broad energy region is required to the contrary, we need to lengthen the magnetic period and the high-energy region should be covered by high-harmonic radiation. It should be noted, however, that we would lose the brilliance overall, especially in the high energy region because of two effects. One is the reduction of the number of periods and the other is the shrinkage of the energy region covered by the fundamental radiation. The most straightforward way to fix the problem is to adopt a revolver undulator, which accommodates more than one magnet arrays with different magnetic periods on a rotary girder. It should be noted, however, that applying this concept to the cryo-undulator requires a lot of efforts. Instead, we consider a new cryo-undulator scheme that enables a wide-band energy coverage with the fundamental radiation, which is based on a “composite-period undulator” concept recently proposed in SPring-8.

In SPring-8 BL08W, the wiggler is used as a light source to provide hard X-ray photons with energies up to 300 keV. As stated in Section 6.1.1, wigglers would not be adopted in SPring-8 II without any special reason. For hard X-ray applications like those in BL08W, utilization of high-harmonic UR would be recommended instead of WR. As shown later, high-harmonic UR is expect to provide much better performances than WR does in terms of both the brilliance and flux with much less heat load. If a variable polarization option is requested as in BL08W, we need to consider a novel undulator magnet configuration together with its operation, because the phasing motion (moving the undulator magnet array in the longitudinal direction) under the ultra-high vacuum condition is not feasible with the existing undulator magnet configuration. Note that this is not applied to the energy region below 30 keV, where a polarization control technique based on a crystal phase retarder using the Bragg diffraction has been realized and routinely used.

6.1.3 Soft X-ray Beamline

The soft X-ray beamline (SXBL) covers the photon energy region between 250 eV and 2 keV. The electron beam energy of 6 GeV would be so high that a high K value would be required to lower the fundamental energy of UR down to 250 eV. Assuming a conventional undulator, this results in a significant increase in the intensity of high harmonic radiation, which turns to heat sources in optical elements. The undulator specification should be defined to avoid such a heat load problem especially in SXBLs. In addition, the ID should have a capability to control or at least select the polarization state unlike those in HXBLs, because the polarization control technique, such as the crystal phase retarder in the hard X-ray region, is not yet established in the soft X-ray region. In general, the so-called APPLE-II undulator can be selected as an ID to produce a variety of polarization states. It should be noted, however, that the heat load in the linear polarization mode of this type of undulator can be significantly large when a high K value is applied, and thus it is impractical to be adopted in SXBL for polarization control.

In order to solve the problem, special undulators designed to reduce the heat load have been installed in SPring-8 and successfully operated for many years: the helical undulators for circular polarization and figure-8 undulators for linear polarization, which are supposed to be the main IDs as well in SXBLs in SPring-8 II. In the former, the helicity of circular polarization can be flipped by the phasing motion. In the latter, the vertical and horizontal linear polarization can be switched by changing the undulator gap and an adequate selection of the photon energy. It is not possible, however, to switch from the linear to circular polarization only with these undulators, and thus each SX beamline in SPring-8 is currently confined to either of the linear- or circular-polarization application except a few exceptions.

Recently, a new undulator scheme, which enables the polarization control with the heat load being kept low, has been proposed in SPring-8. In this scheme, it is possible to switch the device from the helical undulator to the figure-8 undulator with a simple procedure. Furthermore, the linear polarization angle is selectable in the figure-8 undulator mode. In SPring-8 II SXBLs, this undulator scheme could be introduced for a flexible control of polarization states.

The helicity switching speed in the above scheme cannot exceed 0.1 Hz at the moment, because it is carried out mechanically, namely by the phasing motion. In several experiments such as those with magnetic circular dichroism, the signal-to-noise ratio of the measurement strongly depends on the switching speed. For the purpose of improving the speed, a fast helicity switching system, composed of two undulators with opposite helicity and five kicker magnets, has been developed in SPring-8 and implemented in BL25SU, which is currently operated at the maximum switching speed of 10 Hz. In order to install the same system in the normal straight section of SPring-8 II, which is about 2 m shorter than that of SPring-8, we would need to make the kicker magnets much more compact than the current ones.

Although the above helicity switching system with kicker magnets has been operated for more than 10 years and is reliable enough, it is not easy to achieve a switching speed higher than the current maximum value of 10 Hz. In order to aim at a much higher switching speed, a new helicity switching system called a segmented crossed undulator, which has been installed and under commissioning in SPring-8 BL07LSU, is considered to be an option for the faster helicity switching. It is composed of several undulator segments, half of which produce linear polarization and the rest produce vertical polarization, and electromagnet phase shifters placed in between. In order to apply this concept to the normal straight section of SPring-8 II, downsizing the electromagnet phase shifters and shortening the magnetic period would be crucial, because all these components should be packed into the limited space of 3.7 m. If necessary, a possibility of modifying them to in-vacuum devices needs to be considered.

6.1.4 New Category Beamline

In addition to the IDs installed in the normal straight sections, two new types of IDs are supposed to be installed in the storage ring, with which new category beamlines would be available to users in SPring-8 II. One is a mini undulator to be installed in the arc section of the storage ring and the other is a damping wiggler to be utilized as a mean to reduce the beam emittance. Detailed specifications of these IDs are described in the followings.

Mini Undulator Beamline

In one of the drift spaces between magnets in the arc section, there is a slot where a short ID may be installed as a light source for a new beamline, which is referred to as Mini Undulator Beamline (MUBL). The maximum space allowed for the ID, which is decided from the geometrical condition of the adjacent magnets, is supposed to be about 0.5 m and the minimum vertical aperture is expected to be 9 mm. Considering the fact that IVUs require extra spaces with a length of several hundreds of millimeters for installation of RF transitions to connect the magnet end with the vacuum duct smoothly and electrically, out-vacuum undulators (OVUs) are more attractive than IVUs in terms of the net magnet length, even at the expense of the minimum gap. As an example, we assume an OVU with a period of 38 mm. The net magnet length is supposed to be 0.4 m and thus we have a number of periods of 10. The minimum gap and the resultant maximum K value are expected to be 13 mm and 2.3, respectively, which is large enough to smoothly connect the brilliance and flux curves between UR harmonics. Note that the possibility of adopting IVUs should be explored if the RF transitions can be much more compact than the current design.

Damping Wiggler Beamline

As mentioned in Section 5.2.1, damping wigglers are planned to be installed in the storage ring in order to reduce the emittance, which also could work as light sources for new beamlines referred to as Damping Wiggler Beamlines (DWBLs). For an efficient emittance reduction, the magnetic field and period of the damping wiggler should be as strong and short as possible (see Section 5.2.1 for details). Assuming a permanent magnet wiggler operated at room temperature, the possible magnetic field strength is at most 2.1 Tesla. The shortest period to achieve the maximum field of 2.1 Tesla at the gap of 12 mm is 200 mm, resulting in the K value of 37. The total wiggler length is decided to satisfy the requirement on the radiation damping for the emittance reduction and supposed to be several tens of meters, which is too long to be constructed in a single body and thus divided into several units with a typical length of 3 m. The arrangement and locations of these wigglers should be carefully decided with many points taken into account, such as the number of beamlines and handling of the large radiation power.

6.1.5 Expected Light Source Performances

In this section, the light source performances expected in the typical beamlines described in the previous sections are presented. The accelerator and ID parameters to be used in the calculations are summarized in Tables 6.1 and 6.2. Note that the stored current of the SPring-8 II is assumed to be 300 mA, while that of the current SPring-8 is 100 mA.

As shown in Table 6.2, two sets of parameters have been prepared for HXBL. “HXBL-A” is an alternative to the standard undulator beamline of SPring-8, while “HXBL-B” is a beamline dedicated to the confined energy region (14.4~26 keV), and, to be specific, is an alternative to BL35XU.

The light source performances have been calculated with these parameters and compared with those in SPring-8 BL03XU (standard beamline), BL35XU, BL25SU (soft X-ray beamline), BL08W (wiggler beamline), BM1 (bending magnet beamline). All the calculations have been carried out using the SR calculation code SPECTRA [1].

Brilliance

Figure 6.1 shows the brilliance available in the existing beamlines in SPring-8 and proposed beamlines in SPring-8 II as a function of the photon energy. The current values in SPring-8 are indicated by dashed lines, while those expected in the corresponding beamlines in SPring-8 II are indicated by solid lines with the same colors. We expect an improvement of brilliance by 2 and 3 orders of magnitude in SXBL and HXBL, respectively. Also note that even in MUBL, the brilliance is expected to be higher than that of the standard beamlines in SPring-8. On the other hand, almost no improvement is found in the wiggler beamline. This is a consequence of the

Table 6.1: Accelerator parameters used in the calculations. "Section" in the twiss parameter list denotes the location in the storage where a light source is installed.

(a) Beam Parameters

Beam Energy (GeV)	6
Natural Emittance (pm·rad)	35
Coupling Constant	0.02
Energy Spread	0.0011
Stored Current (mA)	300

(b) Twiss Parameters

Section	β_x (m)	β_y (m)	α_x	α_y	η_x (m)	$\eta_{x'}$
(a)	1.07	1.43	0	0	0	0
(b)	9.09	12.3	-8.40	7.15	0.020	0.018
(c)	1.07	1.43	0	0	0	0
(d)	0.29	17.1	-0.54	-0.055	0.0035	-0.0047

fact that the wiggler is an incoherent light source and the reduction of the beam emittance does not necessarily result in the improvement of brilliance. It is now clear that the use of wiggler as a light source in SPring-8 II should be avoided as long as possible, if no special reason exists.

Available Flux

Figure 6.2 shows the comparison of the available flux, i.e., the total flux integrated over the whole solid angle. In the bending magnet beamline, a horizontal angular acceptance of 0.1 mrad has been assumed for the photon beam extraction. Note that the same angular acceptance has been assumed in the wiggler beamline as well, because the angular divergence of WR is extremely large and it is thus impractical to gather all the photons and irradiate to the sample.

The improvement of the available flux from the existing values is not so significant compared to that of the brilliance, because it is independent of the electron beam emittance. Even so, we can expect an improvement by one order of magnitude in the undulator beamlines thanks to the increase in the average current and number of magnetic periods. Note that the flux available in MUBL is much larger than that in BM1 in SPring-8 under the supposed condition, and thus we can conclude that the construction of MUBL is useful in terms of the available flux as well as the brilliance.

Table 6.2: ID parameters used in the calculations. See the caption of Table 6.1 for the meaning of "Section".

Beamline	Source Type	Period (mm)	Min. Gap (mm)	Max. K	Length (m)	Section
HXBL-A	cryo-undulator	14.4	2	2.74	3	(a)
HXBL-B	cryo-undulator	10.2	2	1.61	3	(a)
SXBL	Helical Undulator	75	12	4.15	3	(a)
MUBL	Planar Undulator	38	13	2.3	0.38	(b)
DWBL	Damping Wiggler	200	12	37	3	(c)
BM	Bending Magnet	-	-	(0.7 T)	-	(d)

Spatial Coherence

The spatial coherence of SR is usually characterized by the so called coherent fraction $p_{x,y}$ defined as

$$p_{x,y} = \frac{\lambda/4\pi}{\sqrt{\sigma_r^2 + \sigma_{x,y}^2}\sqrt{\sigma_{r'}^2 + \sigma_{x',y'}^2}},$$

where σ_r and $\sigma_{r'}$ denote the source size and angular divergence of radiation emitted from a single electron when passing through an undulator, $\sigma_{x,y}$ and $\sigma_{x',y'}$ denote the beam size and angular divergence of the electron beam in the horizontal and vertical directions at the source point (undulator center), respectively. The coherent fraction corresponds to the M^2 factor in the laser optics and has the maximum value of 1, with which radiation can be focused to the size determined by the diffraction limit using the ideal optics.

Figures 6.3(a) and (b) show the comparison of the coherent fraction in the horizontal and vertical directions, respectively. In the horizontal direction, we can expect an improvement by one (SXBL) or two (HXBL) orders of magnitude. On the other hand, the improvement is not so significant in the vertical direction, because the coherent fraction is already close to 1 especially in the lower energy region. It should be noted that the wiggler beamline has a coherent fraction much lower than 1 in any case, reflecting the fact that the wiggler is an incoherent light source.

Heat Load

In addition to the light source performances described above, the heat load should be also investigated as explained in Section 6.1.1, in particular, in the undulator beamline. Figure 6.4 (a) shows the total radiation power as a function of the fundamental energy in the undulator beamlines except MUBL. Similar to the available flux, the radiation power would increase by nearly

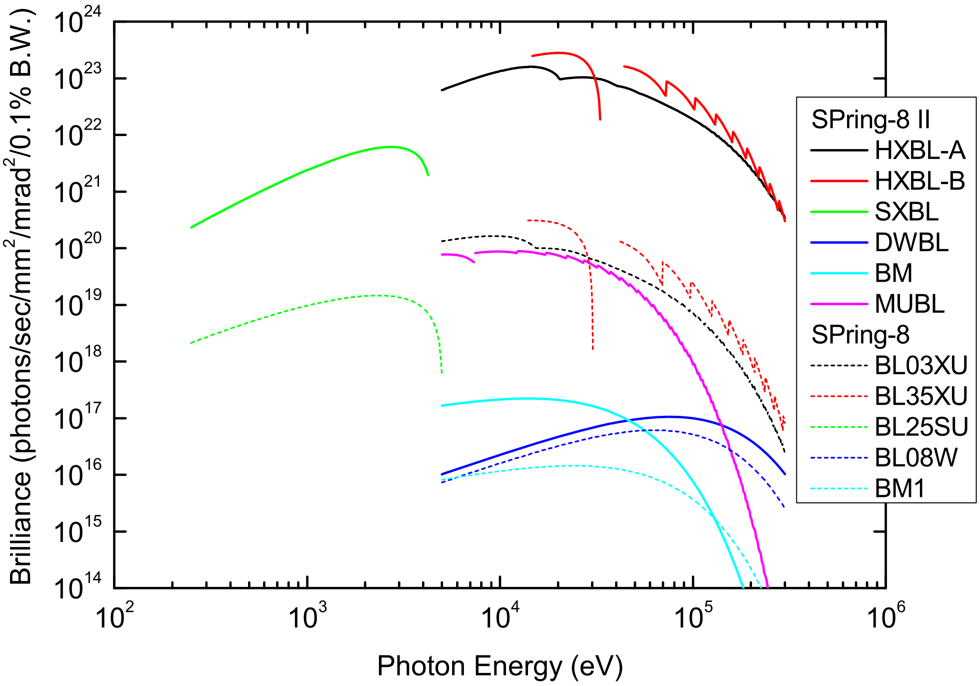

Figure 6.1: Comparison of the brilliance curve available in the existing beamlines in SPring-8 and proposed ones in SPring-8 II. Peak values at respective harmonics are plotted in the undulator beamline, while a spectrum obtained at the maximum K value is plotted in the wiggler beamline. The stored current of 300 and 100 mA are respectively assumed for SPring-8 II and SPring-8.

one order of magnitude because of the increase in the average current and number of periods. It is thus important to carefully design the high-heat load components in the front end section.

Concerning the heat load on optical elements such as the mirror and monochromator, we need to check the partial radiation power passing through the XY slit to eliminate the off-axis power. The calculation results are plotted in Fig. 6.4 (b) as a function of the fundamental energy. The aperture size of the XY slit is assumed to be four times the photon beam size at the fundamental energy so as not to lose the available flux too much. The partial radiation power in SPring-8 II beamlines is found to be at most double of that in the corresponding beamlines in SPring-8, which means that the heat load on optical elements is less problematic than that in the front end section. From the above discussions, it is clear that the heat load reduction using the XY slit works better in SPring-8 II than in SPring-8 thanks to the lower electron beam emittance. It should be noted, however, that the heat load is still larger than the current values and the cooling system of optical elements should be considered carefully.

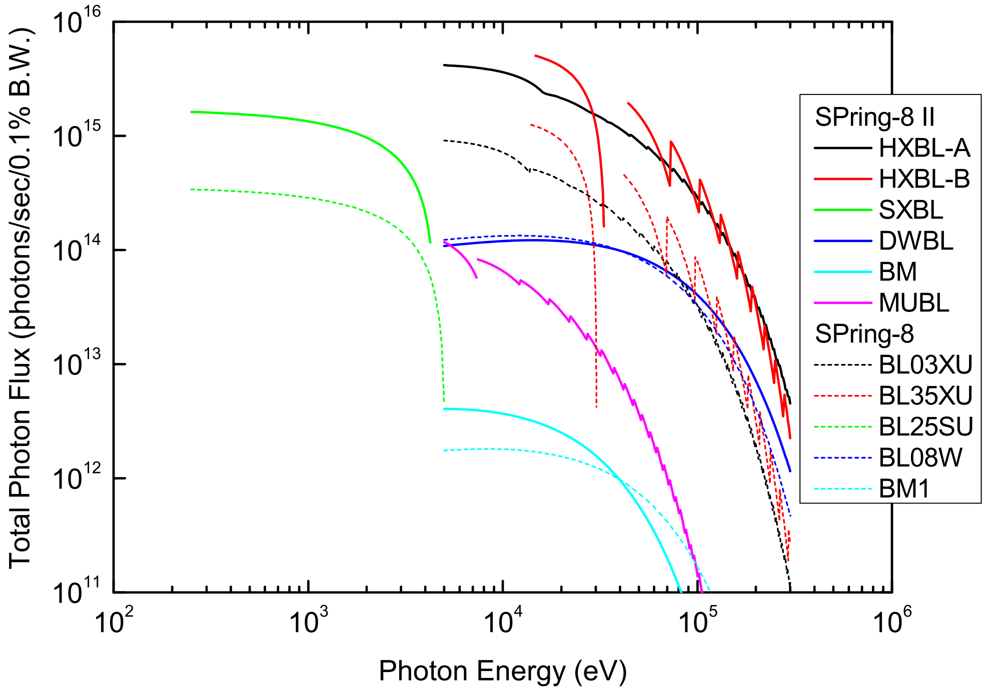

Figure 6.2: Comparison of the flux available in the existing beamlines in SPring-8 and proposed ones in SPring-8 II. The stored current of 300 and 100 mA are respectively assumed for SPring-8 II and SPring-8.

6.1.6 Recycle of the Existing IDs

Although more than 30 IDs have been installed in SPring-8, they cannot be reused in SPring-8 II without modifications mainly because of two reasons. Firstly, the straight section length, which is 5.7 m in SPring-8, will be shortened to 3.7 m to allow the multi-bend lattice configuration for the ultra low emittance ring. Secondly, undulator parameters such as the magnetic period and minimum gap are supposed to be changed. For the total cost reduction, however, we have to recycle the components of existing IDs as much as possible. For example, the SPring-8 ID mechanical frame is composed of three units with a length of 1.5 m, and thus can be decomposed and reassembled to a new mechanical frame with the total length of 3.0 m using two of three units. For this to be applicable, the length of the space in the both ends of the ID, which is occupied by several components and currently 1.2 m long, should be shrunk down to 0.7 m. In particular, beam position monitors (BPMs), which are now working as part of an interlock system for the electron beam trajectory error, are to be excluded from the components installed in the ID straight section, by integrating their functions into other BPMs being distributed over the storage ring.

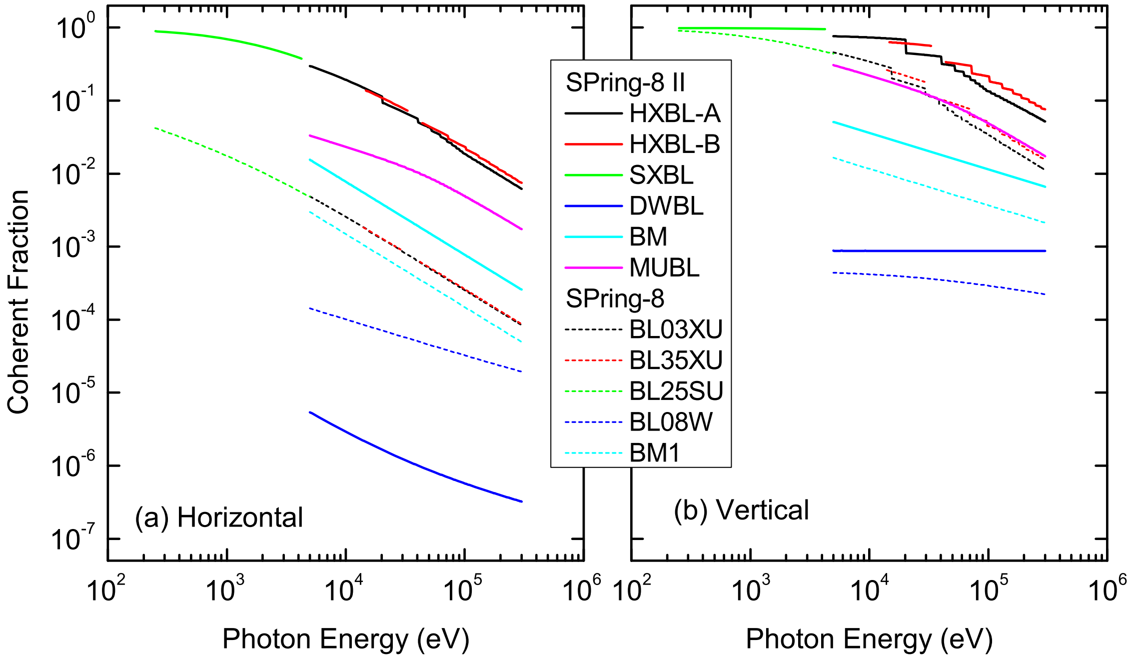

Figure 6.3: Comparison of the coherent fraction in the (a) horizontal and (b) vertical directions.

6.1.7 Beam Stabilization

It is expected in SPring-8 II that a high-flux and nano-focusing beam will be available by introducing a nanometer-focusing mirror and de-magnifying the light source directly without any virtual source in the beamline (see Section 6.3.3). On the other hand, this would impose that the electron beam characteristics at the source point (undulator center) should be extremely stable not to spoil the focusing performance. We have three relevant factors to take care concerning the undulator operation: residual field integral, natural focusing and radiation loss, which can be varied when opening and closing the undulator gap.

The variation of field integral leads to the beam-orbit fluctuation and thus spoils the pointing stability of the photon beam. In SPring-8, it is already corrected by adjusting the current of the steering coil installed in the both ends of the ID based on a feed-forward table created in advance and we shall investigate the scheme to improve the correction resolution and reliability if necessary. The variations of natural focusing and radiation loss cause fluctuations in betatron function and beam emittance, which result in the variations of the beam size and angular divergence. In principle, they can be compensated by adjusting the current of the quadrupole magnets and the gap of the damping wigglers. It is thus important to discuss the correction procedures and its implementation, including its necessity.

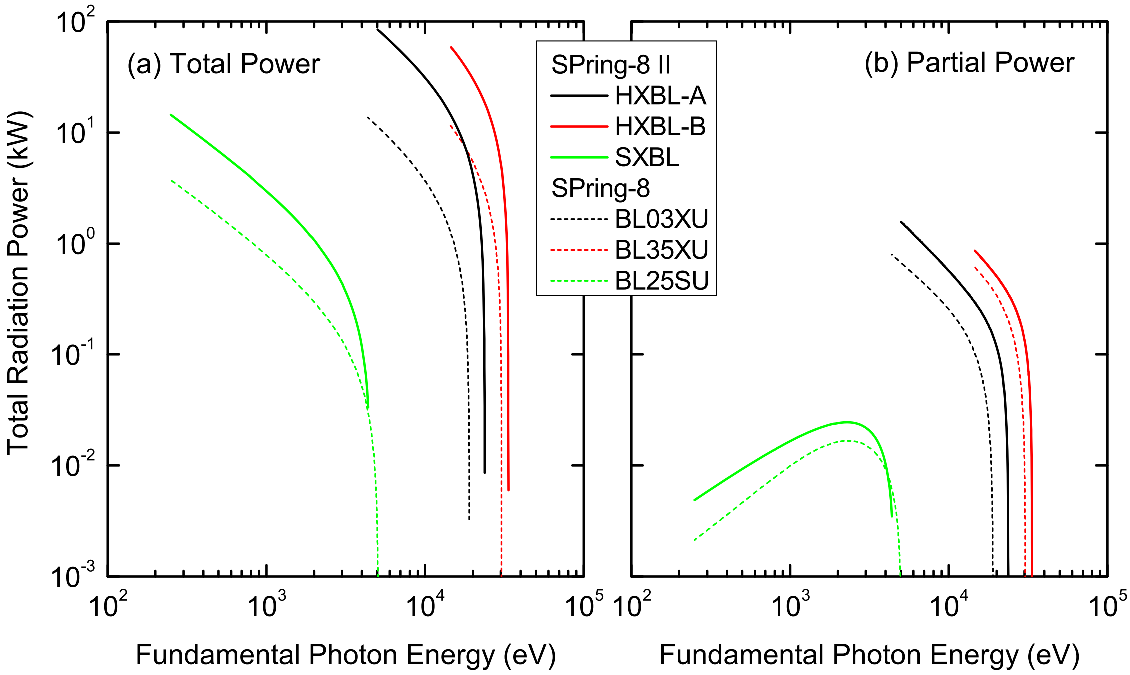

Figure 6.4: Comparisons of the heat load: (a) total radiation power and (b) partial radiation power passing through the XY slit. See text for details. The stored current of 300 and 100 mA are respectively assumed for SPring-8 II and SPring-8.

6.1.8 Summary

In this section, the basic policy to define the ID specifications and expected optical performances have been presented. It should be noted that they are based on the state-of-the-art technologies and ideas currently available, and thus can be modified further according to the progress of the ID technology and theory.

6.2 Front end

The photon beams are transported through the front-end section connecting the light source and the X-ray optics of the beamline, where unwanted heat components in the original radiation is eliminated. Another important function of the front-end section is to monitor the beam position of the radiated X-rays. In the SPring-8 upgrade plan, two key developments in the front-end components will be indispensable: (1) high-heat-load handling, and (2) fast beam-position monitoring technologies.

6.2.1 Handling of high heat load

Newly-developed cryogenic undulators with a short period and a narrow gap would be installed in the upgraded SPring-8 storage ring to dramatically enhance the photon flux. These new undulators would considerably increase the total radiation power as well. Therefore, the front-end section of SPring-8 II beamlines should be designed to eliminate the higher heat load adequately. Otherwise, the heat load onto the downstream X-ray optics would be too high and their designs would be severely restricted. Thus the increase of the heat-load capacity of the front-end components is an unavoidable issue. We are currently performing studies on the following issues.

1. Thermal limitation of the existing high heat load components, made of dispersion-strengthened copper with ultra-fine particles of aluminum oxide and oxygen-free copper
2. Volumetric heating technology
3. Reducing the thermal contact resistance in junctions of photon absorbers
4. Development of multifunctional components (e.g. integration of a fixed mask and a photon absorber)
5. Development of “speckle-free” X-ray windows with a high heat-load resistance

These investigation will be continued until a solution is achieved where the heat load from the high-power undulators could be safely handled. Another important issue is to tune the performances of the high-heat-load components for different light sources, *i. e.* standard undulator, mini-undulator, and bending magnet. The light source of each beamline is optimized to the required photon energy range, energy bandpass, photon polarization, and so on. The period, number of period, total length, minimum K values, correspondingly the resulting radiation power, are different at each beamline.

6.2.2 Pulse-by-pulse monitoring of X-ray beam position

As discussed in Section 3.1, clarification of the time-evolution of physical and biological phenomena would be one of the main scientific targets using the upgraded SPring-8. These studies use the short-pulse characteristics of the X-ray beam and a pump-probe scheme. For such studies, “pulse by pulse” stability of the X-ray beams would be required in addition to the long-term stability that has been established in SPring-8. For pulse-by-pulse diagnostics of the X-ray beam position, a fast beam-position-monitor device is needed. We have been developing a new detector head with a photocathode made of a micro-strip line structure that is capable to work in the GHz range. With the detector, the beam position of individual X-ray pulses (separation of 2 ns) was successfully measured. An evaluation study at a bending magnet beamline showed a good performance with resolutions in position of $\lessapprox 10\ \mu$m, in intensity of $\lessapprox 1\%$, and in time of $\lessapprox 10$ ps. The heat load resistance of the device remains to be an unresolved issue. When the heat load resistance is improved, the detector with a micro-strip line structure would be a promising fast beam-position monitor device that may be installed in the undulator beamlines at SPring-8 II.

Further, correlation analysis between the electron and photon beam positions would allow us to stabilize the X-ray beam more accurately and reliably. A beam position diagnostic system that simultaneously determines the positions of the electron beam in the storage ring and the X-ray beam at the beamline would be introduced at SPring-8 II.

6.3 X-ray optics

SPring-8 II will allow pioneering studies in a wide range of research fields as discussed in Chapters 3 and 4. The enhanced brilliance and flux of the X-ray beam will push the studies requiring high sensitivity and efficiency. Development in optics for the upgraded SPring-8 is important to efficiently deliver high quality radiation to the sample. A mission of the optics in SPring-8 II is to concentrate as many photons as possible into real or reciprocal space with the appropriate size for each experiment. The X-ray beam should be highly tunable since the required beam sizes may range from square millimeter to square nanometer. To provide an extremely stable beam is another big issue. In this section, we describe the basic specifications of the X-ray optical components for SPring-8 II standard undulator beamlines. Requirements for optics in mini-undulator beamlines and bending-magnet beamlines would be much more relaxed. Optical components for these beamlines may be designed with small modifications of those in the standard undulator beamlines.

6.3.1 Monochromator

Double-crystal monochromators will be used in most standard undulator beamlines in SPring-8 II, as have been in SPring-8. Silicon- or diamond-single crystals are selected as the monochromator crystals, producing monochromatic X-rays between 4 and 40 keV with an energy bandwidth of $\Delta E/E \approx 10^{-4}$. The basic mechanical design of the monochromator remains unchanged from that currently adopted in SPring-8. The stability and radiation tolerance would be the major issues that needs to be improved to an ultimate level for various scientific research to be successfully conducted.

Mechanical stability

Excellent mechanical stability in the monochromator is highly required, particularly for experiments using a nano-focused X-ray beam. At SPring-8 II standard undulator beamlines, an X-ray flux of 10^{14} photons/s could be focused in an area of 50×50 nm^2 by directly demagnifying the light source using KB mirrors (see Section 6.3.3). There would be a great progress in photon flux density of 70,000 times from the case of SPring-8, where the beam size was too large and a demagnification of a small virtual source, slits or pinholes, is often used for X-ray focusing. In the direct demagnifying scheme, the monochromator is the only optical component between the light source and the focusing mirror. Angular vibration of the monochromator crystals, if exists, could significantly affect the effective focused beam size. The angular vibration of a monochromator crystal has to be suppressed to within 0.1 μrad (0.02") for 50×50 nm focusing. Possible sources of the angular vibration are, for example, circulation of coolant inside crystals, vibrations of vacuum systems, air conditioners, and the vibrations of the floor. Currently, the angular vibration of the monochromator was estimated to be approximately 1 μrad in June 2011, still one order of magnitude larger than the required level. Further R&Ds to improve the mechanical stability are ongoing.

Thermal stability

Various kinds of heat transfer occur inside and outside of a monochromator chamber. The strategy to tackle thermal stability problems is divided into two approaches, namely, an effective cooling of the monochromator crystals and a stable temperature control of the whole equipment.

Most of the power from the incident radiation is transformed into heat in a narrow area on the irradiated surface of the first monochromator crystal. Without sufficient cooling, thermal deformation of the crystal lattice would result in a deteriorating performance of the monochromated X-ray beam. Cooling systems must be designed with a careful consideration on the following three important factors; thermal conductivity, thermal expansion, and heat transfer. In SPring-8 undulator beamlines, the cooling of the silicon crystals is carried out by two kinds of coolant: cryogenic liquid nitrogen or water at room temperature. In the cryogenic cooling system, silicon crystal blocks are mounted on copper plates cooled with liquid nitrogen. Silicon crystals have a good performance with respect to thermal conductivity and thermal expansion near the liquid nitrogen temperature. However heat transfer from the crystal is not very good as the crystals are cooled indirectly. On the other hand, in the water-cooling system, the crystal has a pin-post shaped water channel just beneath the irradiated surface for efficient heat exchange. The pin-post channel causes a turbulent water flow that increases the heat transfer rate. Both cooling systems could effectively work for an incident radiation power of 500 W and a power density of 500 W/mm^2. However, the power and power density expected from the light sources of SPring-8 II is twice of this level, 1 kW and 1 kW/mm^2, therefore an enhancement of cooling power is required.

All three processes, thermal conductivity, thermal expansion, and heat transfer, need to be optimized in the crystal cooling system adapted for SPring-8 II. A simple solution is to use both the cryogenic cooling and the heat-transfer channel. A new design, different from the conventional pinpost shape, would be required. Additionally, the flow rate of liquid nitrogen needs to be increased from the current level of 4 L/min to 10 L/min, to reduce the pressure drop within the transport pipes inside and outside of the monochromator.

When the temperature inside a monochromator is not stable, thermal deformation of the stepper stages in the monochromator results in a drift in beam intensity over time. Secondary radiation generated at the first crystal also acts as a heat source, while liquid nitrogen works as a negative heat source. We have successfully controlled the temperature of SPring-8 monochromators with a fluctuation of only 0.1 °C (peak-to-valley) using additional heaters and radiation shields. Further improvement would be needed.

Radiation torelance

Since the monochromators in SPring-8 II will be subjected to exposure of the X-ray flux several times higher than that of current SPring-8, the radiation damage to various parts of the monochromator would be considerably higher. Especially, the resistance to high-energy radiation of coating on electric wires would be one of the most serious problems. To solve this problem, we plan to cover the wires with effective radiation shields and to use wires coated with polyimide.

6.3.2 Mirrors for higher-harmonic rejection

X-ray beams obtained with a crystal monochromator inevitably contain higher-order harmonic X-rays aside from the first-order X-rays. Total reflection mirrors are widely used to remove the higher-harmonic X-rays. The glancing angle of an incident beam is as small as a few milliradians when a total reflection mirror is used. This results in a large irradiation footprint at the surface of the mirror, significantly reducing the power density on the mirror surface. For this reason, the cooling of such a total-reflection mirrors is much easier than that of monochromator crystals. A configuration of beamline optics, in which a total reflection mirror is placed in front of a monochromator, is a reasonable solution for SPring-8 II to handle the high power radiation, instead of the present configuration, in which the monochromator is used as the first optical component, in SPring-8 beamlines.

6.3.3 Nanometer-focusing mirror optics

Focusing of X-rays down to a size of 1 nm is a challenge of the current synchrotron radiation facilities. The present record in the smallest X-ray beam size is 7×8 nm [2], which RIKEN and Osaka University have recently accomplished at SPring-8 using the precise multilayer mirrors in the Kirkpatric and Baez (KB) configuration. SPring-8 is one of the leading center for the X-ray nano-focusing techniques [3]. The diffraction limited light source available at SPring-8 II would accelerate the developments to realize the ultimate X-ray nanobeams, aiming towards the size of molecules.

In addition to the benefit for the ultimate nanofocusing, the extremely high brilliance of SPring-8 II light source will significantly increase the photon flux in an X-ray focus spot with the size of a few tens of nanometer. Figure 6.5 illustrates the remarked difference of the photon flux obtained in a beam spot, from $40{\times}40$ nm^2 to $1{\times}1$ μm^2, before and after the upgrade. Calculation was made assuming the X-ray energy of 15 keV and the X-ray optics similar to those at present SPring-8 undulator beamline, where a 100 nm focusing has been recently achieved. The optics include the standard double-crystal monochromator and the KB focusing mirrors. It is assumed that crossed-slits would be inserted as the virtual source downstream of the monochromator when the source size is too large for focusing by demagnifying itself. In the figure, the flux curves suddenly drop at the focus size thresholds of 100×100 nm^2 for SPring-8 and at 50×50 nm^2 for SPring-8 II. These threshold sizes are determined by the source size. Direct focusing (demagnifying) of the light source is used for the focus size larger than these thresholds, where nearly all the flux from the source could be collected in the focus spot. A small virtual source (a few micrometer square), on the other hand, is needed to achieve the focus size smaller than these thresholds, significantly reducing the flux in the focus spot. The focus size achieved by demagnifying the source is much reduced from 1 μm to 50 nm in horizontal direction due to the much smaller source size after the upgrade. Thus, the increased brightness and the reduced source size of the SPring-8 II significantly enhances the X-ray intensity at the focus spot. The enhancement of the flux is estimated to be 300 times for the 100 nm square-focusing, 70,000 times for 50 nm square, and 14 times for 40 nm square.

Developments of new focusing optics is currently ongoing: multilayer KB mirrors [3] and a single mirror with an ellipsoidal surface profile, with an enlarged numerical apertures, will be promising to further reduce the focus size and enhance the available focused beam flux. Additionally, multilayer mirror would offer an option for a wide-bandpass monochromator to increase the photon flux by one order of magnitude with a reasonable bandpass. In addition, we shall continue to make every effort to stabilize the optical components. For focusing systems, a stability of pico-meter-order is needed for providing the stable nanometer-size of X-ray focused beams.

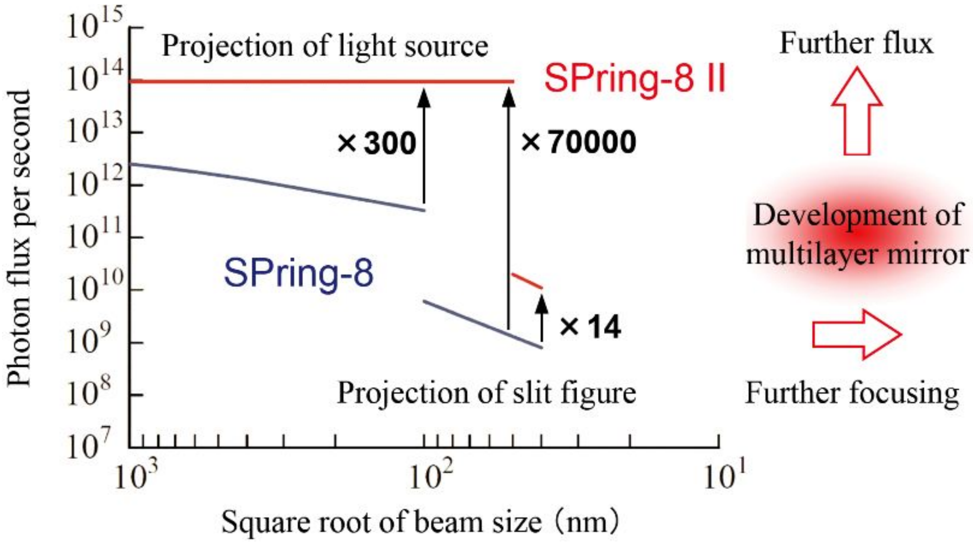

Figure 6.5: Comparison of the X-ray photon flux available in a nanometer-focused spot at the standard undulator beamlines of SPring-8 and SPring-8 II (left). Development of multilayer fabrication will be a key issue to further enhance the flux and to reduce the focused spot size (right).

6.3.4 X-ray beam position monitor

The angular vibration of a monochromatic X-ray beam has to be be suppressed within 0.1 μrad for nano-focusing experiments, as shown in Section 6.3.1. Real-time detection of the position and direction of the X-ray beam with a feedback stabilization system is planned to be installed at SPring-8 II standard undulator beamlines. This system consists of two X-ray beam position monitors placed just behind the monochromator and just before the focusing mirrors, at a typical distance of 30 m. The required angular resolution of 0.1 μrad may be achieved using the two monitors that have a positional resolution of 1 μm separated by this distance.

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