Insertion Devices for Third-Generation Light Sources

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Abstract

By the introduction of the concepts of short-period undulators or minipole undulators, we can raise the upper limit of the fundamental photon energy of undulator radiation up to 400 keV region without any unreasonable heat load, so that the utilization of synchrotron radiation without any wiggler may be possible. Furthermore, we can bring down the lower limit of the fundamental without either unreasonable heat load or unnecessary higher harmonics by adopting helical undulators.

1. INTRODUCTION

Synchrotron radiation (SR) from bending magnets has wide-band characteristics ranging from far infrared to x-ray region, so that one can obtain a monochromatic light at any wavelength by using an appropriate monochromator. Although it is obvious that such characteristics have initiated the advance of synchrotron radiation science, it should be noted that the spectral band is too wide compared to that of the resolution of the monochromator. As a result, the monochromatized light may be accompanied with unwanted stray or higher order lights and the optics may be damaged by heat load derived from the source itself. Such heat load may be called as unreasonable heat load because it is brought mainly by unnecessary spectral part of the source. Therefore, we can say that the spectral property desired for synchrotron radiation source is not wide-band, but narrow-band characteristics with wide tunability, which is one of the motivations for the development of insertion devices, particularly undulators.

The undulator, a single-mode source in the transverse phase space, generates a single cone of radiation. The angular spread, $\sigma_{r'} = \sqrt{\lambda/L}$ [1] where L is the length of the undulator, is so narrow that the property of the radiation may be greatly improved by lowering beam emittance. On the other hand, the bend source is regarded as a multi-mode source since the radiation is composed of many small unit sources being distributed in the orbital plane. The angular radius of the unit source is given approximately by $\sigma_{r'} = 0.3\sqrt{\lambda/\rho\gamma^{-1}}$ [2] where ρ is the radius of the bending magnet. The wiggler, another kind of insertion device, is regarded as a superposition of many bend sources. Therefore, the essential nature of the radiation is the same as that of the bend source. The efficiency of the improvement by lowering emittance is not so high compared to the case of undulator radiation. Furthermore, the optics may be damaged by unreasonable heat load.

Nevertheless, for the utilization of very high energy radiation, the use of high field wigglers is generally

considered. In case of 3rd-generation light sources, however, the above solution is thought to be undesirable from the view point of heat load problems as well as cost performance, because most of construction cost or man power has been shared for obtaining undulator radiation with high brilliance in 3rd-generation light sources, where high brilliance or high coherent flux should be pursued by undulators without any unreasonable heat load. From this point of view, this paper describes what kind of insertion devices should be installed in 3rd generation light sources.

2. UNDULATORS FOR HARD X-RAY

A. Short-period undulators

Since the minimum vertical vacuum gap is allowed as ~ 25 mm in case of ordinary storage rings, the minimum magnetic gap of undulators may be ~30 mm taking the thickness of the vacuum chamber into account. To obtain the tunable range of one octave, the maximum deflection parameter, Kmax, is required as 1.5, which may be satisfied by the undulator with the period length of 50 mm. In the near future, the SR community can use the beam energy up to 8 GeV (SPring-8[3]) except for the large high-energy machines, Tristan-MR[4] and PETRA[5]. Therefore, the fundamental of undulator radiation covers the photon energy range up to 10 keV with the conventional undulator described above. Taking the use of higher harmonics up to 5th into account, the range can be extended up to 40 keV. However, it should be noted that unreasonable heat load may increase. For example, the first and third harmonics may contribute to unreasonable heat load when one uses the 5th harmonic. We hope that such an energy range can be covered by the fundamental. Therefore, we have to develop short-period undulators with the period length below 30 mm, which requires magnetic gap shorter than 10 mm. There are three approaches for realizing such short-period undulators, thin-wall chamber, flexible
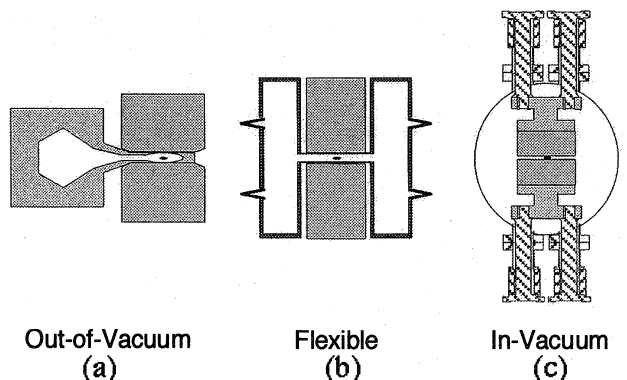

Out-of-Vacuum	Flexible	In-Vacuum
(a)	(b)	(c)

Fig.1. Examples for short-period undulators, (a)thin-wall chamber[6], (b) flexible chamber and (c)in-vacuum types.

Table 1. Spectral properties of the minipole undulator, MPU, compared to those of the wiggler, W. The calculation is made from the beam parameters of SPring-8. The unit of brilliance is photons/s/mm^2/mrad^2 in 0.1% bandwidth.

	λu mm	N	B or K	Σ_x μm	Σ_y μm	$\Sigma_{x'}$ μrad	$\Sigma_{y'}$ μrad	Brilliance at 200keV	P_{total} kW	$P_{density}$ kW/mrad^2
W	90	50	B=1.25 T	810	51	360	30	1.3E17	28.2	270
MPU	3	166	K=0.17	131	2.6	53	27	1.7E18	0.72	41

chamber and in-vacuum types.

At Advanced Photon Source, APS, the vacuum chamber with very thin wall of 1 mm has been developed for realizing a short magnetic gap of 14 mm[6] as shown in Fig.1-a. In the Top-off operation proposed at APS[7], the beam loss originated in narrow aperture may be negligible since the loss can be easily compensated by very short interval of injection. So, much shorter gap will be realized.

The vertical aperture required for the stored beam are different among the various operating modes of the ring. In case of the conventional undulator with a vacuum chamber of fixed type, the inner aperture of the chamber should be designed taking the maximum case into account. So, the minimum gap is generally limited to be a conservative value. On the other hand, in the undulator with a flexible vacuum chamber as shown in Fig.1-b, the inner aperture can be varied according to the operating modes of the ring. Therefore, the very short magnetic gap can be realized according to the beam lifetime required. The first undulator of flexible type has been developed by the joint work with LBL and SSRL[8]. Recently, the simpler one has been developed at HASYLAB[9].

In case of in-vacuum type as shown in Fig.1-c, the permanent magnets are arranged in the ultrahigh vacuum. Therefore, the magnetic gap can be made much shorter than the two types mentioned above because the device has no vacuum chamber in the gap. Since it is easy to obtain a short gap below 10 mm, undulators with the short period below 30 mm can be realized. However, there are two serious problems to be overcome. One is outgassing from the surfaces of the rare earth magnets due to their pourus structure. The other is irreversible demagnetization of the magnets during ultrahigh vacuum (UHV) bakeout

at the temperature higher than 100℃. The former can be solved by the coating on the magnet surface by nickel electroplating or titanium nitride ionplating. To solve the latter, we have to adopt permanent magnets having very high coircivity. In addition to that, it is necessary to apply aging process to the magnets at the temperature somewhat higher than that of UHV bakeout[10]. The first in-vacuum undulator has been developed at KEK[11]. The minimum gap is achieved as 10 mm without any beam loss.

Thus, short-period undulators with a period length below 30 mm can be realized. With a beam energy of 8 GeV for example, the fundamental of undulator radiation can cover the energy range up to 40 keV. Taking the use of higher harmonics up to 5th into account, the available photon energy can be extended up to 80 keV.

B.Minipole undulators

To obtain very high energy photons above 100 keV with the beam energy of 8 GeV, the use of wigglers may be generally considered. As mentioned above, however, this solution may bring unreasonable heat load in the optics. To avoid such a problem, the minipole undulator concept has been proposed(Fig.2). This concept, derived from that of micropole undulators with the period length of submilimeters[12], aims at the compatibility with the storage ring operation. Therefore, the period length will be chosen as several milimeters with the magnetic gap above 1 mm. As a matter of course, such a device should be of in-vacuum type without any vacuum chamber in the gap. To obtain stable orbit with a very narrow aperture, the betatron function should be designed to be very small, typically 0.1 m, with additional quadrupole magnets located at the both ends of the device. Such a strong
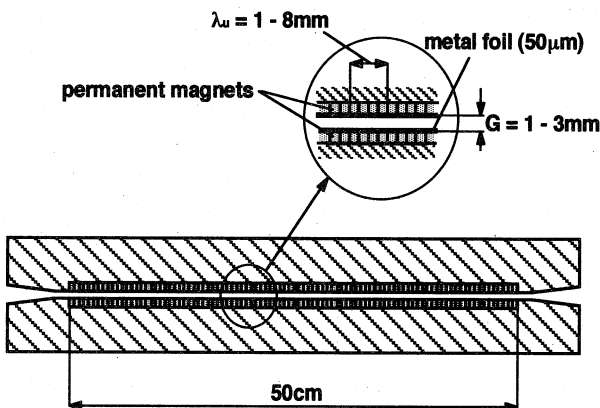
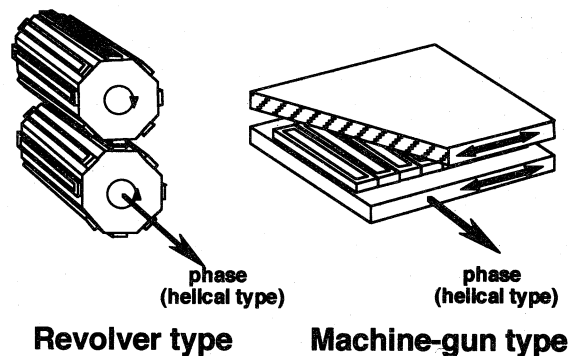Fig.2   Schematic illustratiobn of a minipole undulator.

Fig.3   Schematic illustration of Multiundulator systems for minipole undulatrors, revolver and machine-gun types.

SPring-8, E=8GeV, I=100mA

minipole undulators
(Revolver type)
λ_u = 2 - 8mm, L = 50cm
P_T= 0.4- 0.7kW, P_D= 40- 70kW/mrad^2

Gap=1 - 3 mm

wigller
λ_u= 9cm, N=50, B=1.25T
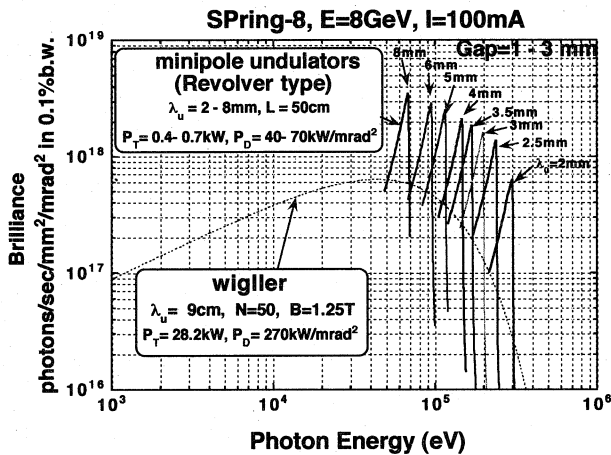P_T= 28.2kW, P_D= 270kW/mrad^2

Fig.4 Calculated spectral brilliance from an example of a
revolver composed of 8 minipole undulators with
different periods from 2 mm to 8 mm. The spectrum
from the wiggler is also shown for comparison.

focusing means that the device length should not be so
long, typically 0.5 m. However, the number of periods is
very large because of very short-period, so that high
brilliance of the radiation can be expected.

Table 1 shows spectral properties of the minipole
undulator with the period length: 3 mm, the number of
periods: 166, and the K value: 0.17, compared to those of
the high field wiggler with the period length: 120 mm, the
number of periods: 50, and the magnetic field: 1.25 T. As
shown in the table, the calculated brilliance of the minipole
undulator is higher by one order than that of the wiggler,
and their total fluxes are not so different. In addition to
that, the total radiated power or power density of the
minipole undulator is much lower than that of the wiggler.
Although the ring operation may be difficult with minipole
undulators, they are very practical for the x-ray optics.

However, minipole undulators have a disadvantage;
the K value is much lower than unity, which means that
the tunable energy range is not so wide. To solve this
problem, the multi-undulator system, revolver or machine
gun, should be adopted (Fig.3). Figure 4 shows the
calculated spectral brilliance from an example of a revolver
composed of 8 minipole undulators with different periods
from 2 mm to 8 mm. In the figure, the spectrum from the
wiggler is shown for comparison. The spectral
performances of the minipole undulators is found to be
much better than that of the wiggler in the photon energy
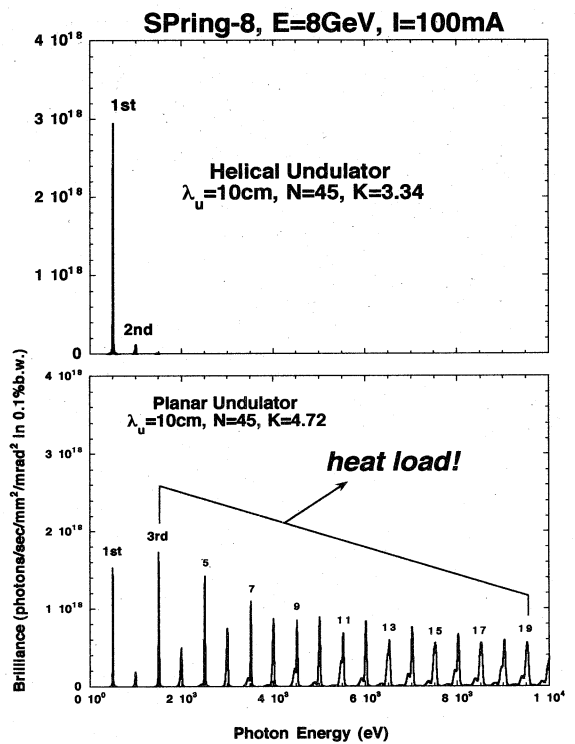region from 70 keV to 300 keV.

Fig.5 Spectral brilliances obtained from the planer and helical
undulators having the same period length of 10 cm and
producing the fundamental with the same photon energy.

3. UNDULATORS FOR VACUUM ULTRAVIOLET RADIATION

Since the SR community can use the beam energy up to 8
GeV, it is easy to obtain the fundamental by conventional
undulators in the vacuum ultraviolet region below 4 keV.
However, another heat problem may appear. As an
extreme case, we suppose that one desires 500 eV photons
with the beam energy of 8 GeV. Table 2 shows the spectral
parameters of 3 possible undulators, U100, U500 and
HU100, with the same device length of 4.5 m. Although
the brilliance of the planer undulator, U100, is as high as
1.5×10^{18}, the power density is so high due to the high K
value that the optics may be damaged. On the contrary,
the power density of the other planer undulator, U500, is
very low. However, the brilliance is only 2×10^{17} due to
the small number of periods, which is a nonsense result
since this value can be obtained easily in 2nd generation
light sources. The last undulator, HU100, is of helical
type with the same period length as that of U100. The

Table 2. Spectral parameters of three possible undulators, U100,U500 and HU100 for producing the
fundamental with the photon energy of 500 eV. The calculation is made from the beam parameters
of SPring-8. The unit of brilliance is photons/s/mm^2/mrad^2 in 0.1% bandwidth.

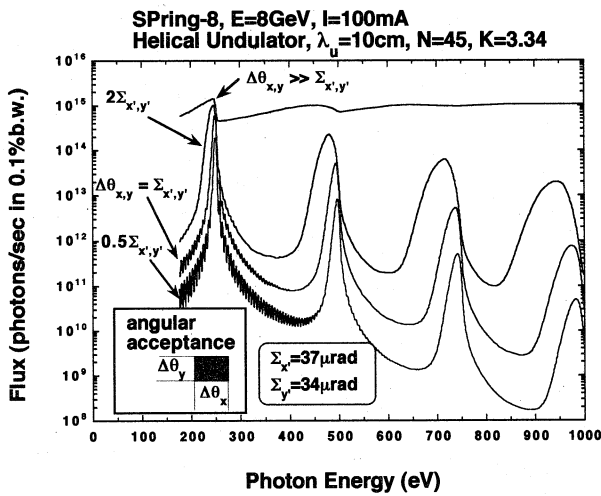| Name	Type	Polarization	λ_u mm	N	K	Brilliance at 500eV	P_{total} kW	$P_{density}$ kW/mrad^2
U500	planar	linear	500	9	1.7	2.4E17	0.023	1.3
U100	planar	linear	100	45	4.7	1.5E18	4.6	100
U100	helical	circular	100	45	3.34	3.0E18	4.6	0.6

Fig.6   Spectral flux obtained from HU100 for various angular acceptances. The horizontal or vertical angular divergence of the source are denoted as Σ x',y'.

Beam Energy (GeV)

Fig.7   Available photon energy range of various kinds of undulators for the beam energies from 1 GeV to 10 GeV.

brilliance is 3×10^{18}, twice higher than that of U100. Nevertheless, the power density is much lower by 2 orders. To reveal the above inconsistency, the comparison is made in Fig.5 between the spectral brilliances obtained from both undulators. As shown in the figure, the spectrum of U100 has many higher harmonics while in the spectrum of HU100 most of the higher harmonics disappear, which is the reason why helical undulators have very low power density. It is obvious that the higher harmonics appearing in the U100 spectrum contribute to unreasonable heat load.

In case of helical undulators with high K value, most of the radiated power derived from the higher harmonics is existing off axis. Therefore, an appropriate slit system is required to eliminate not only the heat load but the higher harmonics. The wide acceptance dose not confirm the increase of the fundamental flux, but brings unnecessary higher harmonics as shown in Fig.6, where the flux spectra obtained from HU100 are shown for various angular acceptances.

4. SUMMARY

We can raise up the upper limit of the fundamental photon energy to adopt short-period undulators or minipole undulators as shown in Fig.7 where the available photon energy range of various kinds of undulators are shown for the beam energies from 1 GeV to 10 GeV. For example, 40 keV or 400 keV photons can be obtained by short-period or minipole undulators, respectively, with the beam energy of 8 GeV (SPring-8). Furthermore, we can bring down the lower limit of the fundamental without either unreasonable heat load or unnecessary higher harmonics by adopting helical undulators. Although at present such a merit cannot expected in the utilization of linearly polarized radiation, the novel undulators, which can generate linearly polarized VUV radiation with low on-axis power density, are under development at SPring-8.

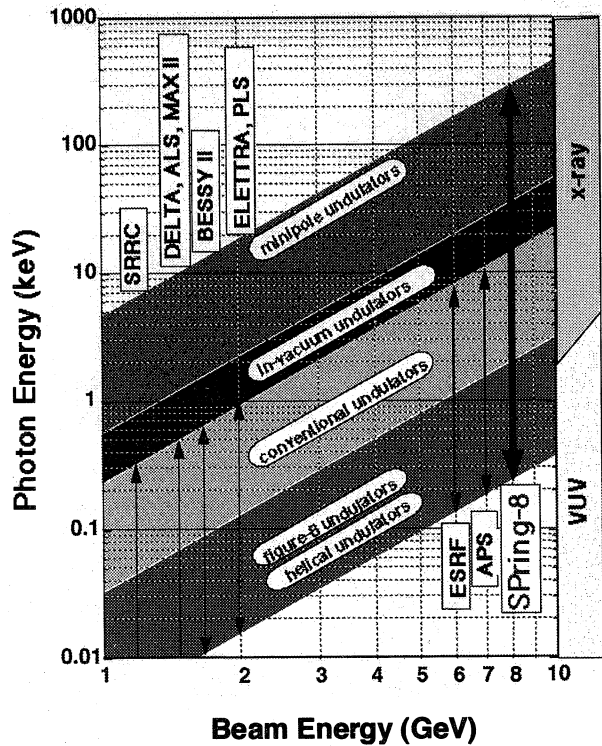The pursuit for pure radiation (monochromatic radiation without any higher harmonics) is very important for 3rd generation light sources because the next generation light source is aiming at the production of laser light in the VUV or x-ray region.

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