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Present Status of SPring-8 Insertion Devices

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According to the general policy, namely, the pursuit of pure radiation without any unreasonable heat load, the construction of various insertion devices has been scheduled at SPring-8. Most of them are of the in-vacuum type, which makes it possible to realize short-period devices, so that the fundamental of undulator radiation may be obtained in the hard X-ray region. In addition, undulator radiation in the soft X-ray range down to 100 eV is available by introducing helical or figure-8 devices having low on-axis power density, which is very beneficial for the optics, gratings or mirrors. A brief overview of the insertion devices at SPring-8 is presented with the initial commissioning results.

Keywords: undulators; in-vacuum; polarization; independent tuning.

1. Introduction

Since SPring-8 has the highest beam energy, 8 GeV, among the third-generation light sources in the world, it should be regarded as an excellent light source. However, one may point out that such a high-energy beam would result in an unreasonable heat load on the optics unless well designed insertion devices were installed (Kitamura, 1994). Prior to designing the undulators for SPring-8, we proposed a general policy for the insertion device program. (i) Hard X-rays of several 10 keV should be obtained by the first harmonic of undulator radiation since the coherence property of undulator radiation is very important. (ii) The pursuit of high brilliance or high-energy photons should not result in an unreasonable heat load. (iii) Exotic devices, helical, elliptical, vertical and figure-8 undulators, should be positively introduced. However, they should be designed to have good magnetic field properties. (iv) Tuning of undulator radiation, or changing the insertion-device gap, can be made at any time. In other words, undulators should be operated simultaneously with the scanning of the monochromators.

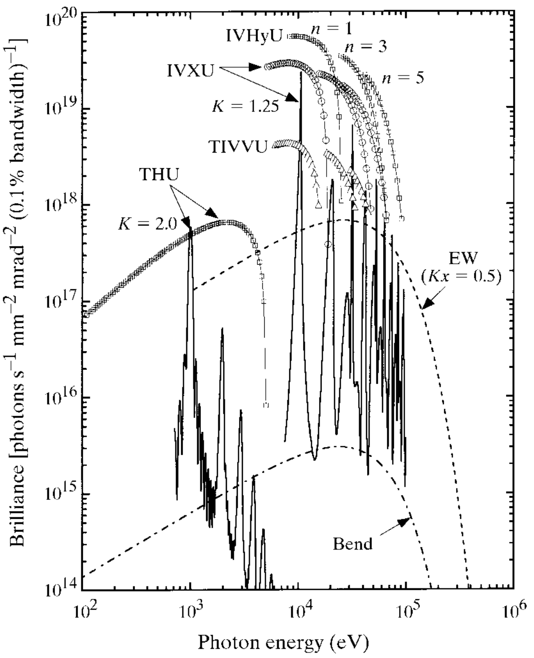

Figure 1
Calculated spectra of the radiation from the various sources at SPring-8. The following beam parameters are assumed: emittance = 6 nm rad, emittance coupling = 2% and beam current = 100 mA. The type of each source appearing in the figure is assigned in Table 1.

According to the above policy, the construction of various insertion devices has been scheduled for SPring-8, which was designed to have 38 long straight sections for insertion devices. At present (August 1997), four devices (three standard in-vacuum X-ray undulators, IVXUs, and a tandem in-vacuum vertical undulator, TIVVU) have been commissioned successfully; a further three (two standard IVXUs and an elliptical wiggler) were installed into the ring this summer, and another four (a twin helical undulator, a figure-8 undulator, an in-vacuum figure-8 undulator and an in-vacuum hybrid undulator) are under construction. In this paper we describe the performance of these devices and the results of the commissioning.

2. Summary of the insertion devices at SPring-8

Table 1 presents an outline of the beamlines attached to the insertion devices at SPring-8. The 34 straight sections for insertion devices each have a length of 6.6 m (between the edges of the quadrupole magnets). Considering the focusing characteristics, however, they can be classified

Table 1
Insertion-device beamlines at SPring-8.

Considering the focusing characteristics, the straight sections can be classified into two categories: high-β and low-β sections. The former/latter is assigned to the odd/even number beamline. The types of the devices are denoted as EW, elliptical wiggler; IVXU, in-vacuum X-ray undulator; F8, figure-8 undulator; IVF8, in-vacuum figure-8 undulator; THU, twin helical undulator; TIVVU, tandem in-vacuum vertical undulator; IVHyU, in-vacuum hybrid undulator. Polarization (P): H, horizontal; V, vertical; C, circular.

Location	Beamline	Type	P	λ_u (cm)	N	G_{min} (mm)	B_{max} (T)	K_{max}	1st (keV)	3rd (keV)	5th (keV)	Installation
BL08IN	High-energy inelastic scattering	EW	C	12	37	20	1.1y 0.1x	1.1x				Aug 1997
BL09IN	Nuclear resonant scattering	IVXU	H	3.2	140	8	0.82	2.45	4.7–18.5	15.5–51	26–75	Finished
BL10IN	Extremely dense state	IVXU	H	3.2	140	8	0.82	2.45	4.7–18.5	15.5–51	26–75	Aug 1997
BL11IN	JAERI	IVXU	H	3.2	140	8	0.82	2.45	4.7–18.5	15.5–51	25–75	Aug 1998
BL24IN	Hyogo	IVF8	H V	2.6	172	5	1.05y 0.34x	2.6y 1.7x	4.5–20			Jan 1998
BL25IN	Soft X-ray spectroscopy	THU	C	12	2 × 12	20	0.58xy	6.5xy	0.12–45			Jan 1998
BL27IN	Soft X-ray photochemistry	F8	H V	10	44	20	1.0y 0.25x	9.3y 4.6x	0.1–5.8			Jan 1998
BL39IN	Physiochemical analysis	IVXU	H	3.2	140	8	0.82	2.45	4.7–18.5	15.5–51	26–75	Aug 1997
BL41IN	Biocrystallography	IVXU	H	3.2	140	8	0.78	2.32	5.2–18.5	15.5–51	26–75	Finished
BL45IN	RIKEN	TIVVU	V	3.7	2 × 40	8	0.5x	1.7x	6.6–16	20–40	33–70	Finished
BL46IN	R&D for insertion devices	IVHyU	H	2.4	187	5	0.9	2.0	6.6–25	20–70	34–90	Jan 1998
BL47IN	R&D for X-ray optics	IVXU	H	3.2	140	8	0.78	2.45	4.7–18.5	15.5–51	26–75	Finished

into two categories: high-β (β_x/β_y = 24/9 m) and low-β (β_x/β_y = 1/5 m) sections. The former/latter are assigned to the odd/even-numbered beamlines. The beam emittance is designed to be 6 nm rad. When the emittance coupling is assumed to be 2%, the beam sizes and divergences are estimated to be σ_x/σ_y = 380/33 mm and σ_x/σ_y = 16/3.6 mrad for high-β sections or σ_x/σ_y = 77/24 mm and σ_x/σ_y = 77/4.9 mrad for low-β sections. The calculated spectra of the radiation from these sources are shown in Fig. 1, where the beam current is assumed to be 100 mA. The types of sources appearing in the figure are assigned in Table 1. In the following, the characteristics of each device are described briefly.

2.1. *Standard in-vacuum X-ray undulators*

To obtain the first harmonic of undulator radiation in the hard X-ray region, an undulator with a very short period should be developed. However, it is well known that the magnetic field of an undulator depends mainly on the ratio of the magnetic gap to the period length, which means that the very short gap property is essential to realize very short period undulators. Although various designs for such undulators have been proposed so far, an in-vacuum design is considered to be the best solution for the following reasons: (i) the vacuum aperture for the electron beam is almost the same as the magnetic gap, which is particularly important for minipole undulators with a periodic length less than 10 mm; (ii) the magnetic gap or vacuum aperture can be varied according to the various operating modes of the storage ring, which is convenient for improving the performance of the ring.

Thus, we have adopted an in-vacuum design for the X-ray undulators at SPring-8. The important technical points of in-vacuum design are the following. (i) A delicate undulator magnet system should be compatible with an ultrahigh vacuum. To solve this, we have made a titanium nitride (TiN) coating of thickness 5 µm for permanent magnets and adopted special permanent magnets of NdFeB (NEOMAX33UH supplied by Sumitomo Special Metal Company) without any demagnetization during ultrahigh-vacuum bakeout at 403 K for 48 h. (ii) We have to hold the permanent magnets using mechanical clamps,

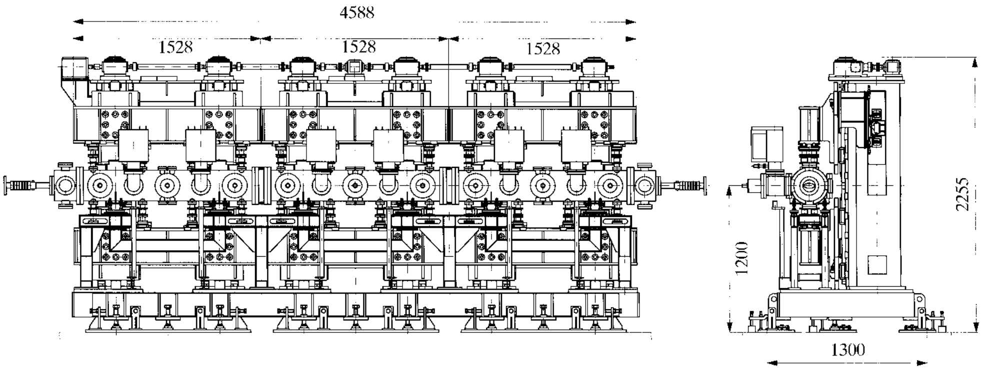

Figure 2
Plan view of the standard in-vacuum X-ray undulator.

because cement or glue is not available in ultrahigh vacuums. (iii) To suppress heating by the image current of the stored beam (Bane & Krinsky, 1993), the permanent magnets should be covered by Cu-plated Ni foils of thickness 50 μm.

The first in-vacuum undulator was developed at KEK (Yamamoto *et al.*, 1992). Although the SPring-8 type is based on the KEK device, we have made miniaturization, simplification, standardization and other improvements. Fig. 2 shows a plan view of a typical SPring-8-type in-vacuum undulator, a so-called standard in-vacuum X-ray undulator, IVXU (λ_u = 3.2 cm, N = 140, $B_{\rm max}$ = 0.82 T, $K_{\rm max}$ = 2.45 at the gap of 8 mm), of pure permanent-magnet configuration (Hara, Tanaka, Tanabe, Maréchal, Okada & Kitamura, 1998). The mechanical part of the device is composed of three identical units each of length 1.5 m mounted on the common base; however, the magnet arrays of length 4.5 m form a single undulator with two pairs of half-magnets at both ends. As shown in Fig. 1, the first, third and fifth harmonics of the radiation from a standard IVXU cover the photon energy ranges from 4.7 keV to 18 keV, up to 50 keV, and up to 80 keV, respectively. At present, three standard IVXUs are in operation.

2.2. *Tandem in-vacuum vertical undulator*

The in-vacuum technology realizes special devices, for example, a vertical undulator generating vertically polarized radiation. In the case of such a device, to obtain a high magnetic field in the horizontal direction the magnetic gap should be set to a very small value. We have constructed a tandem in-vacuum vertical undulator, TIVVU, composed of two in-vacuum vertical undulators in tandem configuration to generate vertically polarized radiation with different photon energies. The periodic length is 3.7 cm with the number of periods of 40 per undulator. This device has a special feature in the magnetic design: a gutter is made in the centre of the magnet array to obtain a wide good field region in the horizontal direction (Tanaka *et al.*, 1998*a*). The first harmonic covers the energy range from 6.6 to 16 keV.

This device is in operation. The attached beamline is designed to make the best use of vertical polarization. For example, a diamond monochromator working as a beam splitter in the horizontal plane has been developed and a preliminary test was made successfully during beamline commissioning (Yamamoto *et al.*, 1998).

2.3. *Elliptical wiggler*

To provide the high-energy inelastic beamline with circularly polarized X-rays in the energy range up to 300 keV, we have constructed an elliptical wiggler having a periodic length of 12 cm with a number of periods of 37 (Maréchal *et al.*, 1998). The device is composed of six magnet arrays. The vertical and horizontal fields are generated by two central and four outer magnet arrays, respectively (Maréchal *et al.*, 1994; Kimura *et al.*, 1996; Hiraya *et al.*, 1998). Each outer magnet array can be translated independently, so that not only the phase of polarization but also the horizontal field may be adjustable. The maximum vertical (B_y) and horizontal (B_x) fields are 1.1 and 0.1 T, respectively. The circular polarization rate, for example, is estimated to be 75% at 200 keV when B_y and B_x are 1.1 and 0.05 T, respectively. This device has been installed already, and the commissioning will be performed in September 1997.

2.4. *Twin helical undulators*

Although various methods for rapid switching of helicity have been proposed so far, we are developing a novel one in which two helical undulators with opposite helicity, so-called twin helical undulators, are used with five kicker magnets. By controlling the operations of these kicker magnets, circular radiation with different helicity would be obtained alternately on the same axis (Hara, Tanaka, Tanabe, Maréchal, Kumagai & Kitamura, 1998). The design goal of switching is 10 Hz. The structure of the undulator magnet is similar to that of the elliptical wiggler except for the phasing method. In the case of the present device, the phasing is made by shifting the central magnet arrays. The periodic length is 12 cm with a number of periods of 12 per undulator. The available photon energy range is from 500 to 5 keV. This device will be installed in January 1998.

2.5. *Figure-8 undulator*

If the first harmonic with low photon energy is desired, we have to apply a high K value. In the case of planar undulators, however, such a high K-value setting results in high power density as well as many higher harmonics, which may damage the optics. On the other hand, in the case of helical undulators, a typical circularly polarized source, the higher harmonics exist off-axis, so that the damage can be minimized using an appropriate slit system. However, some users require linearly polarized radiation with low on-axis power density. This property is very important in some scientific fields, particularly angle-resolved photoelectron spectroscopy. To realize such radiation, we have developed a figure-8 undulator (Tanaka & Kitamura, 1995, 1996). Although this device resembles the SPring-8-type helical undulator, the periodic length of the horizontal field is twice as long as that of the vertical field. Therefore, the electron orbit projected in the transverse plane resembles a figure of 8. As a result, we can obtain linear polarization, not circular polarization. In addition, we can expect the central power density to be very low in a similar way as with helical undulators. However, it should be noted that lower-order harmonics still exist on-axis.

To provide the soft X-ray photochemistry beamline with linearly polarized radiation, we are constructing a figure-8 undulator having a periodic length of 10 cm with a number of periods of 44 (Tanaka *et al.*, 1998*b*). This device will be installed in January 1998.

2.6. *Minipole undulators*

To obtain very high energy photons above 100 keV with a beam energy of 8 GeV, the use of wigglers may be generally considered. However, this solution may bring an unreasonable heat load in the optics. To solve this problem, we have to develop minipole undulators having a periodic length shorter than 10 mm, which means that the magnetic gap is shorter than 5 mm, so that the device should be of the in-vacuum type (Stefan *et al.*, 1995) and the vertical betatron function at the location of the device should be less than 0.5 m. However, such a strong focusing means that the device length should not be so long, typically 0.5 m. Nevertheless, the number of periods is very large because of the very short period, so that high brilliance of the radiation can be expected. At present, there is no straight section with such a low betatron function at SPring-8. In the near future, however, some straight sections will be modified by locating additional quadrupoles to obtain a low betatron function.

Thus, we have made an R&D study on minipole undulators in collaboration with NSLS, Brookhaven National Laboratory. In May 1997, the in-vacuum minipole undulator, having a periodic length of 1.1 cm with a number of periods of 32, was installed in the X-ray ring at NSLS. Commissioning of this device was successfully performed and a minimum magnetic gap of 3.3 mm was obtained (Stefan *et al.*, 1998; Tanabe *et al.*, 1998).

3. Commissioning of the insertion devices at SPring-8

Four in-vacuum undulators (three standard IVXUs and one TIVVU) were installed before the commissioning of the storage ring, which was not disturbed because the gap of each undulator was fully open at 50 mm. After one month, the first undulator radiation was obtained from the standard IVXU for the beamline BL47 on 23 April 1997. All four undulators were commissioned successfully before the summer shutdown. During commissioning, optimization of the steering-magnet current for each undulator was carried out to realize independent tuning as shown in Fig. 3, which presents the fluctuations of the beam positions at nine different locations of the orbit when the gap of the standard IVXU for BL47 was changed from 50 mm to 8 mm. The left-hand or right-hand figure shows the horizontal or vertical beam positions, respectively. As shown in the figures, the fluctuations are well suppressed within 10% of the beam size.

Although the minimum gap of 8 mm was achieved for all the undulators at the stored current of 15 mA, the beam lifetime decreased from 10 to 7 h. This beam loss is thought to be because the present vertical betatron function of 9 m is not optimized for short-gap undulators. The lifetime may be improved by lowering the betatron function down to 2.3 m, *i.e.* half of the device length of 4.5 m.

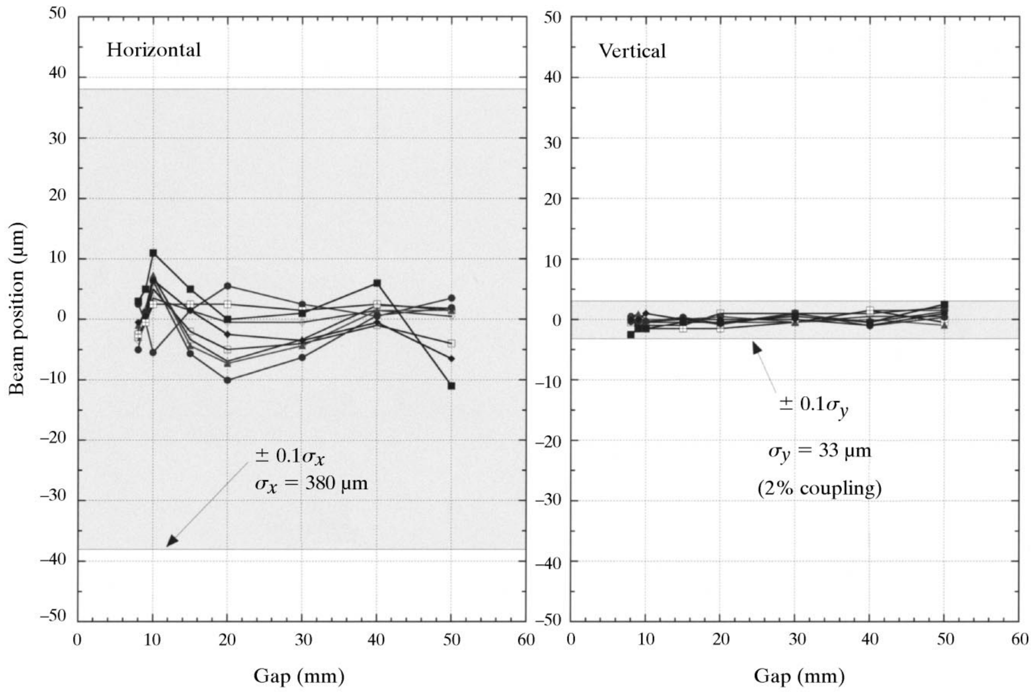

Figure 3
Fluctuations of the beam positions at nine different locations of the orbit when the gap of the standard IVXU for BL47 was changed from 50 mm to 8 mm. The left-hand and right-hand figures show the horizontal and vertical beam positions, respectively.

In the commissioning phase, the beam current was limited to 20 mA according to the radiation safety program. Therefore, heating by the image current was not observed.

4. Conclusions

The first four in-vacuum undulators at the SPring-8 ring were operated successfully. The gap of each undulator was successfully closed to its minimum value of 8 mm; however, the beam lifetime decreased to 70%. It may be improved by lowering the vertical betatron function to 2.3 m, *i.e.* half of the device length. The kick by each undulator was successfully cancelled by steering magnets so that independent tuning is possible. Heating by the image current was not observed because of the low beam current of less than 20 mA.

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