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Undulators at HiSOR – a compact racetrack-type ring

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A compact racetrack-type 700 MeV storage ring (HiSOR) has been constructed at Hiroshima Synchrotron Radiation Center (HSRC). As the ring was planned for synchrotron radiation research on science and technology using VUV to X-rays up to 5 keV with limited size and cost, the ring was designed (i) to realize a high magnetic field (2.7 T) using conventional dipole magnets for higher critical energy, and (ii) to include two straight sections for insertion devices. A linear undulator (25–300 eV) and a new-type helical/linear undulator were installed at the two straight sections. The latter undulator consists of upper and lower jaws, as in a planar undulator; each jaw consists of one fixed magnet array at the centre and two magnet arrays on both sides. By longitudinal displacement of the side magnet arrays, the phase between the vertical and horizontal magnetic fields, and therefore the polarization (right- or left-circular, elliptical, linear) can be selected. The helical/linear undulator gives almost perfect circular polarization at 4–40 eV in the helical configuration without changing the phase of the magnet arrays, as well as linearly polarized light at 3–300 eV in the linear configuration.

Keywords: compact rings; HiSOR; insertion devices; helical undulators; linear undulators; helical/linear switchable undulators.

1. Introduction

The project to build a synchrotron radiation facility at Hiroshima University started in 1982 and was named HiSOR (Hiroshima Synchrotron Orbital Radiation); it was approved in 1995 as construction of the Hiroshima Synchrotron Radiation Center (HSRC) began. Construction of the building, injector, storage ring and four beamlines at HiSOR was completed in March 1997 (Taniguchi & Ghijsen, 1998). Since the HiSOR facility was planned for synchrotron radiation research in science as well as technology using VUV to X-rays up to 5 keV, the ring was required (i) to realize a higher critical energy and (ii) to contain straight sections for insertion devices. In order to fulfil these requirements while keeping the ring size compact, a racetrack-type compact ring (AURORA-2D: 700 MeV) with high-field dipole magnets developed by Sumitomo Heavy Industries (Hori & Takayama, 1996) was chosen as the HiSOR ring (Yoshida *et al.*, 1998). Two undulators, linear and helical, had been planned to be installed at the first phase of HiSOR. During the designing stage of the helical undulator for HiSOR, a helical/linear switchable undulator was chosen as the second insertion device. In the following, the design concept and expected performance of these undulators, especially for the helical/linear switchable undulator, are reported.

Table 1
Parameters of the linear undulator at HiSOR.

Period length (λ_u)	57 mm
Number of periods	41
Total length (including correction magnets)	2354.2 mm
Gap distance	30–200 mm
Maximum magnetic field	0.41 T
Magnet material	Nd–Fe–B (NEOMAX-44H)

2. Design concept

2.1. *Linear undulator*

The linear undulator at HiSOR was designed to satisfy the following requirements: (i) the lowest photon energy range is below 30 eV, (ii) the length of the straight section for the linear undulator is ~2.4 m. As a compromise for minimizing the intensity gap between the fundamental and third harmonics of undulator light and for maximizing the intensity at the high-energy side, the period of the undulator was chosen to be 57 mm. The parameters of the linear undulator are given in Table 1.

2.2. *Helical undulator*

Two research projects that need intense and/or highly monochromatic circularly polarized light are planned at HiSOR. The first one is asymmetric photosynthesis and photolysis of biomolecules that need circularly polarized light at 4–10 eV. The second one is UV emission spectroscopy of magnetic materials and semiconductors that need circularly polarized light at 15–40 eV. Both projects need a high degree of circular polarization. Therefore the helical undulator at HiSOR is required to cover the photon energy ranges for both projects with enough photon flux and a high degree of circular polarization. Also it was desirable to obtain linearly polarized light from the undulator with simple movement of the magnet arrays, because the capability of switching between circular polarization and linear polarization is important when details of the excitation process and of asymmetric photolysis are investigated at the same beamline. Also, not only for these projects, the capability of switching between a helical and a linear undulator is very important for HiSOR, having only two straight sections, because two linear undulator beamlines then become available even if one of them is time-sharing.

Recently, a linear/helical switchable undulator, conceived to obtain almost perfect circular polarization in its helical mode by only changing the gap and without adjusting the phase was designed and installed at UVSOR (750 MeV) by Kimura *et al.* (1996). The capability of producing almost perfect circular polarization at any gap without adjusting the phase is desirable from the viewpoint of experiments. The undulator designed for UVSOR fulfils all requirements for the helical/linear switchable undulator at HiSOR; furthermore, the electron energies of the two rings are quite similar. Therefore the UVSOR helical/linear switchable undulator was selected as the second insertion device for HiSOR. The alignment of the magnet arrays in the helical/

linear undulator at UVSOR and HiSOR is shown in Fig. 1. This undulator consists of magnet arrays at the upper and lower jaws, similar to the planar undulator. However, each jaw consists of three lanes with a fixed lane at the centre and side lanes that slide along the longitudinal direction, as in the elliptical wiggler for SPring-8 proposed by Maréchal *et al.* (1995). These six magnet arrays have the same period and provide only a vertical magnetic field (B_y) when the displacement between the centre lane and the side lanes is zero (phase = 0) and act as a linear undulator in 'linear configuration' as shown in Fig. 1. By sliding the side lanes in such a way that each diagonal pair (upper right and lower left, upper left and lower right) travels in the opposite direction by $\lambda_u/4$ (where λ_u is the period of the magnets), as shown by the 'helical configuration' in Fig. 1, the side lanes provide a horizontal field (B_x) with $\pm\lambda_u/4$ phase difference relative to the vertical field. Right- and left-circular polarization can be switched by changing the sign of the phase difference.

Based on the alignment of the magnet arrays used in the UVSOR undulator, the period length and the shape of the magnet poles of the helical undulator for HiSOR were further modified to

Table 2
Parameters of the helical/linear undulator at HiSOR.

Period length (λ_u)	100 mm
Number of periods	18
Total length (including correction magnets)	1828.6 mm
Gap distance	30–200 mm
Centre-magnet size	30 (W) × 58.5 (H) mm
Centre-magnet groove size	11 (W) × 15 (D) mm
Side-magnet width	50 (W) × 50 (H) mm
Polarization switching time	100 s (right ⟷ left)
Maximum magnetic field in helical mode	0.347 T
Maximum magnetic field in linear mode	0.597 T
Magnet material	Nd–Fe–B (NEOMAX-44H)

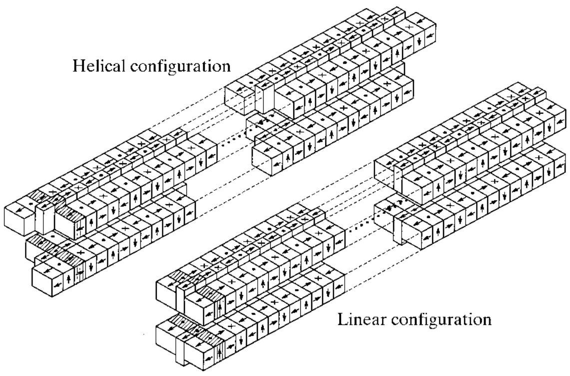

Figure 1
Schematic drawing of the helical/linear undulator at HiSOR. The linear configuration and the helical configuration are shown.

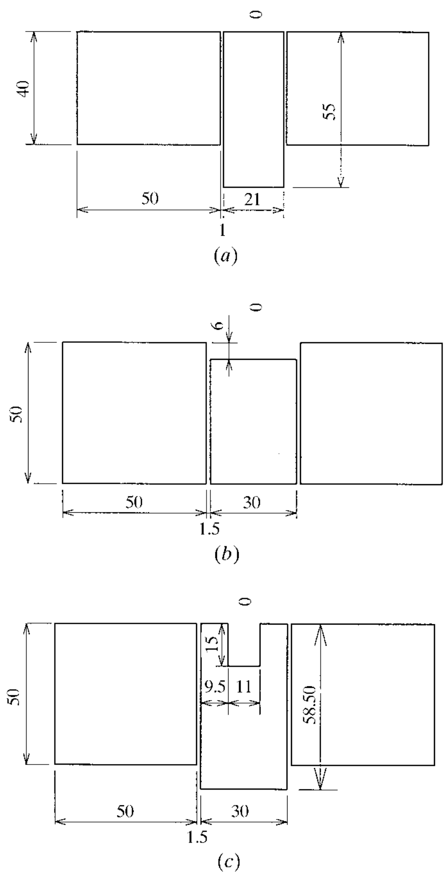

Figure 2
Three types, (*a*) flat, (*b*) offset and (*c*) grooved, of centre and side magnets. The flat-type was used at UVSOR and the other two are designed for HiSOR. The electron beam position at minimum gap (30 mm) is shown for each type.

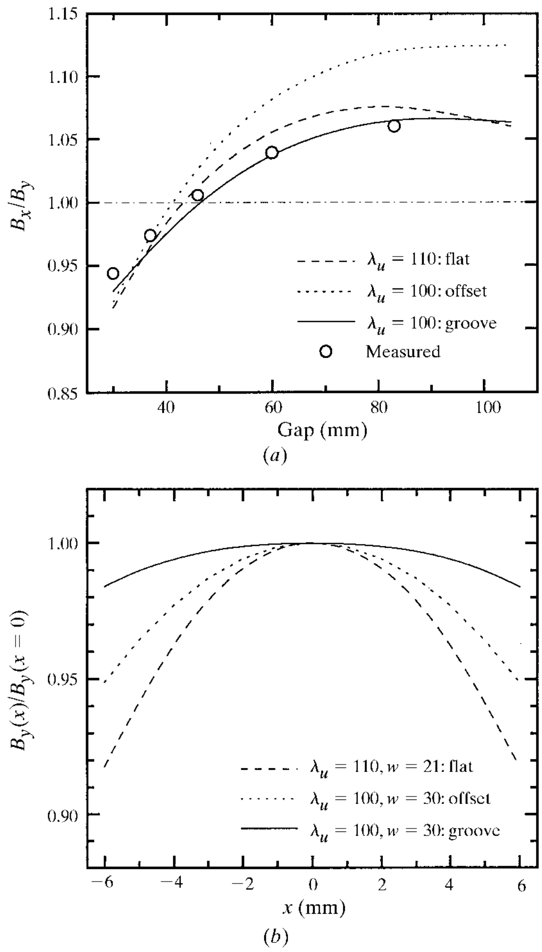

Figure 3
Comparison of the characteristics of the magnetic field for three magnet types: flat, offset and grooved. (*a*) Calculated ratio of horizontal to vertical field (B_x/B_y) as a function of gap distance, and measured value for grooved magnet. (*b*) Calculated transverse distribution of vertical fields (B_y) normalized for B_y (x = 0).

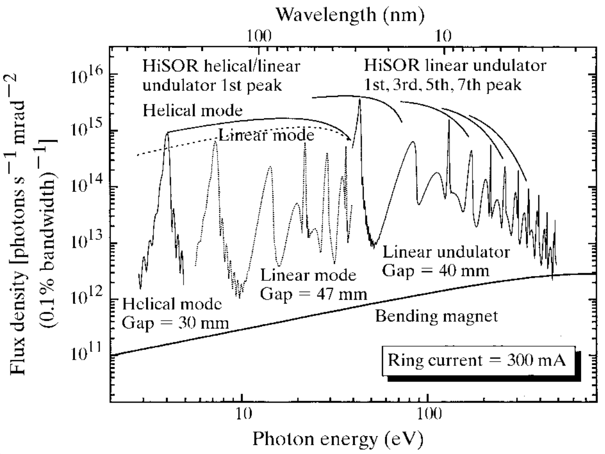

Figure 4
Calculated flux density distribution of two insertion devices and the bending magnet at HiSOR. Flux density spectra at some gaps are shown for the helical and linear modes of the helical/linear switchable undulator, and for the linear undulator.

obtain a higher degree of circular polarization in the photon energy range 4–40 eV. This requires that the ratio of the horizontal field to the vertical field (B_x/B_y) should be almost unity for all gap values. In addition to this requirement for circular polarization, the vertical magnetic field distribution along the transverse axis is required to be as flat as possible. This additional requirement, which is not essential for the UVSOR ring, arises from the fact that the dispersion (η) in the straight section cannot be eliminated for the racetrack-type storage ring. Optimization of the magnet shape to fulfil the above requirements was carried out as follows: (i) maximize the centre-magnet width in order to obtain a flatter distribution of the vertical field, under the limitation of keeping the horizontal field high enough to generate photons at about 4 eV; (ii) reduce the vertical field either by 'offsetting' the centre magnet or by cutting a 'groove' in the surface of the centre magnet as shown in Fig. 2 so that the vertical field is almost equal to the horizontal field. The grooved-shape magnet will also make the vertical field flatter, as pointed out by Tanaka *et al.* (1998). Actually, this procedure was repeated for several period lengths and finally the period length was chosen to be 100 mm.

3. Expected performance

In order to estimate the degree of circular polarization, B_x/B_y at several gaps were calculated for 'flat', 'offset' and 'grooved' magnet shapes and are shown in Fig. 3(*a*). Transverse distributions of B_y for these centre-magnet shapes at minimum gap (30 mm) were also calculated and are shown in Fig. 3(*b*). Although the flat-type vertical magnet (width = 21 mm; used in the UVSOR helical undulator) attains almost 'constant B_x/B_y' for the whole gap range, its transverse distribution of B_y is much sharper than that of the grooved magnet (width = 30 mm). It is clear that the grooved shape is superior than the flat or offset shape from the viewpoints of 'constant B_x/B_y' and 'flat B_y'. Therefore the grooved shape (Fig. 2*c*) was selected for the centre magnet for the HiSOR undulator. The measured value for the actual magnet array (Fig. 3*a*) shows that a B_x/B_y value of 1 ± 0.06 was achieved in the undulator at HiSOR. It is interesting to examine the possibility of 'constant B_x/B_y' for all gap ranges in the APPLE-type undulator (Sasaki *et al.*, 1994) which has only four magnet arrays. The available length for the helical undulator is diminished from the length of the straight section between the Q-magnets (2.4 m) to 1.8 m, because two sets of X–Y stirring magnets are installed at both ends of the helical/linear undulator. The parameters of the helical/linear undulator at HiSOR are given in Table 2. The calculated photon flux densities of the helical mode and the linear mode of the helical/linear undulator, and those of the linear undulator and the bending magnet at HiSOR are shown in Fig. 4. All spectra were calculated by using the *Synchrotron Radiation Calculation Program* (Kitamura, 1993).

4. Summary

A linear undulator and a helical/linear switchable undulator were designed and installed at the compact racetrack-type ring HiSOR. The linear undulator covers the 25–300 eV photon energy region with two to four orders of magnitude higher intensity than the bending-magnet source. The helical/linear switchable undulator at HiSOR was designed with special care for stable operation in both the helical mode and the linear mode used in the racetrack-type storage ring, in which the dispersion at the straight sections cannot be eliminated. In the helical mode, a value of almost unity (1 ± 0.06) of the B_x/B_y ratio and a fairly wide flat region in the transverse distribution of the vertical field are simultaneously realized for the whole gap range by selecting a groove-shaped centre magnet. In its 'helical mode' the helical/linear undulator covers the photon energy range 4–40 eV with almost perfect ($97 \pm 3\%$) circular polarization. Also in linear mode, the undulator acts as a linear undulator or linear multipole wiggler and covers the photon energy range 3–300 eV with about three orders of magnitude higher intensity than the bending source.

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