OBSERVATION OF CIRCULARLY POLARIZED RADIATION FROM MULTIMODE UNDULATOR AT HiSOR

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The linear / helical multimode undulator that is able to produce polarized radiation of any ellipticity operates successfully in Hiroshima Synchrotron Radiation Center. Polarization measurements have been performed for helical mode of undulator using IR-UV polarimeter at the beamline BL9 of the 700 MeV storage ring (HiSOR). High degree of circular polarization has been obtained. The comparison between achieved performance and numerical simulation was made. The main reason of slight distinction between them was found to be in the influence of non-undulator radiation.

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INTRODUCTION

Recently considerable progress was attained in generation of synchrotron radiation in a wide energy range. By now a number of new insertion devices designed for production of high brilliant circular polarized light are suggested and successfully operated worldwide. Among them, circularly polarized photon sources with the capability of switching the polarization are the subjects of interests for many applications, since an essential component for various experiments in biology and materials science is a radiation with variable polarization characteristics. One of such devices, a linear / helical multimode undulator [1] was installed at one of two straight sections of a compact racetrack-type 700 MeV storage ring (HiSOR) of Hiroshima Synchrotron Radiation Center (HSRC) [2]. HiSOR storage ring consists of two 180° normal-conducting bending magnets with maximum magnetic field 2.7 T and four quadrupole magnets. The radius of the electron orbit in bending magnet is R=0.86 m and synchrotron radiation critical energy is 873 eV. The linear / helical multimode undulator was designed to enhance the intensity and degree of circular polarization of photon beam in comparison with those radiating from bending magnet. The first observation of the undulator's radiation shows almost the same performance to the designed values [3]. The HiSOR helical/linear multimode undulator has a similar design to those of the elliptical wiggler for Spring-8 [4,5] and the helical undulator for UVSOR [6]. The undulator consists of upper and lower jaws same as a conventional linear undulator while each jaw is separated into three standard Halbach-type permanent magnet arrays, one fixed magnet array at the center and two outer sliding magnet arrays. Configuration of the multimode undulator allows the continuous transformation from linear mode through elliptical to helical mode by varying of the relative displacement of the outer magnet arrays. Therefore, the linear, elliptical and right or left circular type of polarization can be generated.

Helical mode of HiSOR's multimode undulator (Fig. 1) can be the source of high circularly polarized radiation in UV – VUV energy regions. According to resent experimental requirements, the beamline (BL9) of this undulator was equipped with a 3 m off-plane Eagle monochromator [7]. As a result, the unique combination of the multimode undulator and high resolution Eagle monochromator was obtained. In this article the description of undulator, operated in the helical mode, and analysis of the measurements of radiation polarization properties were carried out.

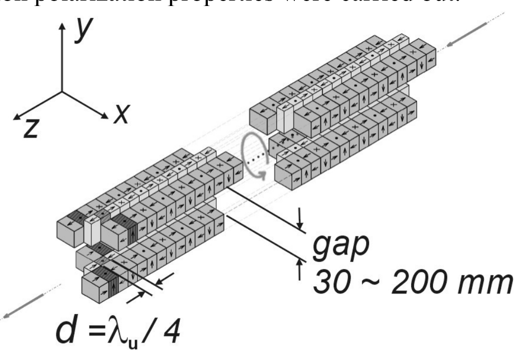

Fig. 1. *Helical mode of the HiSOR's multimode undulator. d is the displacement of the side arrays in reference to their non-shifted position,* λ_u *is the length of undulator period*

HELICAL MODE OF MULTIMODE UNDULATOR

The general parameters of the linear / helical undulator are summarized in Table 1. One can see, that measured magnetic field amplitudes are 1-2% lower than designed values. Therefore, the minimum energy range of the undulator is slightly shifted to the higher energy side.

The analysis of the undulator operating in different modes is given elsewhere [8], so here only the detailed description of the helical mode, that generates circularly polarized light, will be consider (Fig. 1). The multimode undulator was designed to operate in the helical mode with the energy range of 4 - 40 eV and higher degree of circular polarization than 99%. To obtain such a high degree of polarization the vertical to horizontal magnetic field ratio B_y/B_x should be as close to unity as possible for any gap. Moreover, the specific feature of HiSOR is the large horizontal beam emittance. Therefore, the profile width of the vertical magnetic field transverse distribution should be wide enough for the stable operation of the ring. Different shapes of the central magnet were examined according to these two criteria: unity B_y/B_x ratio and flat vertical field profile.

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Finally the "grooved" shape, which is most optimal from the both viewpoints of vertical to horizontal field ratio $\left(B_y \approx B_x\right)$ for any gap and flat distribution of B_y along x-axis, was chosen for the center magnet of undulator see Fig. 2. It is important to note that with the increasing of the gap the behavior of the horizontal and vertical fields amplitudes is slightly different from each other, and, consequently, vertical to horizontal magnetic field ratio is not constant, comprising 1 ± 0.06 for all gap interval. Although in this case the degree of circular polarization is expected to be higher than 99%, further adjustment is possible to obtain unity value of the vertical to horizontal magnetic field ratio for any gap with introducing of slight side arrays shift from helical mode, see Fig. 3. To obtain this figure, value of the side arrays shift d, at which $B_y / B_x = 1$, was calculated for gap interval 30-120 mm. After that for each pair of gap and d the value of deflection parameter K was found and plotted as a 3D scatter. Deflection parameters are defined here by the following standard way $K^2 = K_x^2 + K_y^2$ and $K_{x,y} = 93.4\lambda_u[\mathrm{m}]B_{x,y}[\mathrm{T}]$.

Table 1. *Parameters of the multimode undulator*

Period length, λ_u	100 mm	
Number of periods	18	
Total length	1828.6 mm	
Gap distance	30-200 mm	
Permanent magnet	NdFeB (Neomax 44H)	
Helical mode:	Designed	Measured
Max. magnetic field, T	0.347	0.340
Deflection parameter	4.6	4.37
Energy range, eV	4.2~40	4.4~46
Linear mode:	Designed	Measured
Max. magnetic field, T	0.597	0.593
Deflection parameter	5.6	5.54
Energy range, eV	2.8~350	2.85~355

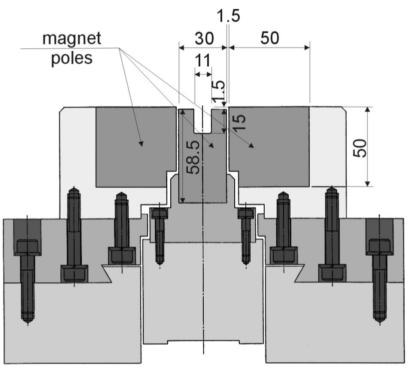

Fig. 2. *Vertical cut of the lower jaw of the linear/helical undulator*

BEAMLINE OPTICS

The undulator is now operating routinely in the helical mode, though changing of the gap is restricted to few times a day. The polarization properties of the fundamental radiation at 30 mm gap were measured at BL9 beamline (Fig. 4a) equipped with a 3-m off-plane Eagle monochromator. The monochromator was designed to perform the measurements with the circular / linear polarized light source in the photon energy region from 4 to 40 eV. Resolving power of this monochromator is very high since the sum of incidence and diffraction angles for grating is equal zero, entrance end exit slits S1 and S2 are displaced sidewise symmetrically on the Rowland cylinder and the angle $\angle S1 - G - S2$ is always equal to 4.5°. Obviously, when undulator radiation and a monochromator are combined, the polarization characteristics of both should be known in order to predict the resulting degree of polarization. The beamline was specially designed to preserve the degree of circular and linear polarization in all working region. For example, Fig. 4b shows the changes of circular polarization at each optical elements of the beamline, which were calculated using the optical constant of materials. It was assumed that the effect on polarization by diffraction at a grating is the same with a mirror (Samson's model) [9].

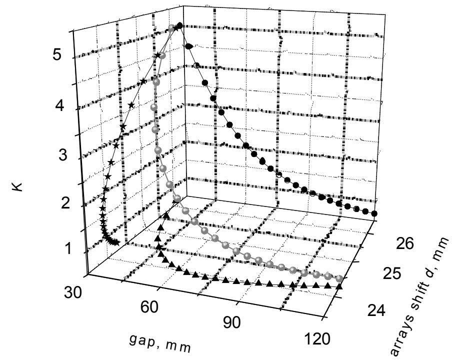

Fig. 3. *Adjustment of helical/linear undulator parameters for obtaining the unity B_y / B_x ratio. K is a deflection parameter of the multimode undulator, obtained for each pair of gap and arrays shift values*

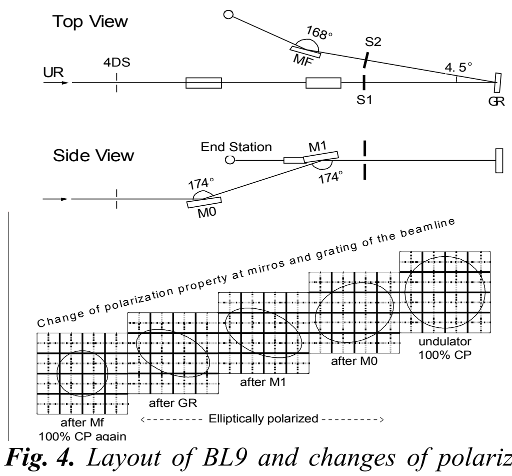

Fig. 4. *Layout of BL9 and changes of polarization property at optical elements of the beamline. 4DS is a rectangular slit; GR is grating with the order of diffraction equal to -1; S1 and S2 are entrance and exit slits; M0, M1 and MF are mirrors*

Calculation shows that absolute degree of circular polarization of incident light from undulator compared to that of the light after the postfocusing mirror (MF) is identical with that of incident undulator radiation within about ~10^{-5} difference. However, the sign of the circular polarization degree is changed by the optical elements of the beam-line to the opposite one, i.e. the incident light with "right" circular polarization after Mf is converted to the light with "left" circular polarization. This phenomenon was confirmed by experiments. The results of the preliminary measurements of polarization type before and after monochromator shows that at side arrays shift $d = \lambda_u/4$ polarization is right circular after undulator and is left circular after monochromator. At side arrays shift $d = -\lambda_u/4$ polarization type reverses.

MEASUREMENT OF POLARIZATION PROPERTIES

In order to measure Stokes parameters (S_0, S_1, S_2, S_3), which completely characterize the polarization state of the light beam [10], polarimeter consisted of phase shifter and linear polarizer is needed. The photon energy for the helical mode of multimode undulator at small gaps is in UV-region. Therefore, it is possible to use transmission type optical elements. The measurements of polarization properties were carried out using the IR-UV four-Stokes polarimeter equipped with a double Fresnel rhomb with retardation angle $\Delta=\pi/2$ at photon energy *4.29 eV* as the phase shifter and a linear polarizer with the extinction coefficient about 10^{-6}. The final light intensity was measured by using of the photodiode detector.

According to [11], intensity of light transmitted by this polarimeter can be expressed by the following equation:

$$I(\alpha,\beta) \sim S_0 + \varsigma S_1 + \tau S_2 + \upsilon S_3$$

where

$$\varsigma = \left(C^2 + S^2\cos\Delta\right)\cos 2\beta - CS\left(1-\cos\Delta\right)\sin 2\beta,$$

$$\tau = -CS\left(1-\cos\Delta\right)\cos 2\beta + \left(S^2 + C^2\cos\Delta\right)\sin 2\beta,$$

$$\upsilon = -S\sin\Delta\cos 2\beta - C\sin\Delta\sin 2\beta.$$

Here $C=\cos 2\alpha$, $S=\sin 2\alpha$, α is a rotating angle of the phase shifter around optical axis, β is that of the linear polarizer and Δ is retardation of the phase shifter. From this equation one can see that in order to obtain Stokes parameters it is enough to measure radiation intensity $I(\alpha,\beta)$ for example at the following six pairs of angles α and β: *(0,0), (0,π/2), (π/4,0), (π/4,π/4), (π/4,−π/4)* and *(−π/4,0)*. After that Stokes parameters can be obtained by substituting the experimental results in the following equation:

$$\begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I(0,0) + I(0,\pi/2) \\ I(0,0) - I(0,\pi/2) \\ I(\pi/4,\pi/4) - I(\pi/4,-\pi/4) \\ \left[I(\pi/4,0) - I(-\pi/4,0)\right]/\sin\Delta \end{pmatrix}.$$

The polarization properties of the light are defined using Stokes parameters as follows:

$$P_c = S_3/S_0,$$

$$P_L = \sqrt{\left(S_1^2 + S_2^2\right)/S_0^2},$$

$$P_U = 1 - \sqrt{P_c^2 + P_L^2}.$$

Here P_c and P_L are degree of circularly and linearly polarization, P_U is the degree of unpolarized light.

Measurements of the radiation properties were carried out for helical mode of multimode undulator at minimum gap for 4-5 eV energy region. At these measurements the size of 4DS was 8x4 mm, width of S1 and S2 was 100 μm and E/ΔE was about 28,000. Example of the experimental results for fundamental peak energy 4.41 eV is shown at Fig. 5. There the current of the photodiode, which is proportional to the intensity of radiation, is plotted for different angles α *vs* rotating angle β of the linear polarizer. In order to decrease the measurement error the photodiode current was measured at many angles β, whereupon it was fitted by sine function and substituted into Eq. 1. The radiation properties derived from the results, presented at Fig. 6, are shown at the first column of the Table 2. Here S_1/S_0, S_2/S_0 and S_3/S_0 are normalized Stokes parameters.

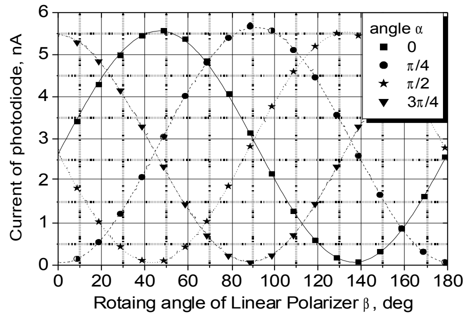

Fig. 5. *Intensity of light transmitted to polarimeter. Current of photodiode at fixed rotating angle α of the phase shifter is plotted as function of rotating angle β of the linear polarizer. Each point corresponds to measured value; each line is curve fitting of the measurement data by using sine wave function*

Table 2. *Stokes parameters of the radiation for 30 mm gap at helical mode of the undulator measured at fundamental peak energy 4.41 eV. 1st column: measurements after monochromator; 2d column: numerical calculation of undulator radiation; 3d column: estimation with taking into account non-undulator radiation. P_c, P_L, and P_U are degree of circular, linear and unpolarized light*

Value	Measured	Calculated	“Pure”
S_1/S_0	-0.045	-0.0465	-0.05
S_2/S_0	-0.0483	-0.00471	-0.051
$P_C = S_3/S_0$	-0.977	-0.998	-0.983
P_L	0.066	0.0474	0.0712
P_U	0.021	0.00071	0.0143

RESULTS AND DISCUSSION

Stokes parameters of undulator radiation were obtained for 30mm gap at helical mode with side arrays shift $d = \lambda_u/4$ at several photon energies around the fundamental peak. The radiation characteristics have been estimated using computer code “Smartwig” [12]. Fig. 6 shows measured (a) and calculated (b) intensities of radiation and the degrees of circular polarization (c). Numerical results of estimation for fundamental peak are shown at the 2d column of the Table 2, in comparison with the measured results, shown at 1st column. One can see, that the high P_c ratio (97.7%) was experimentally obtained at the fundamental peak energy. However, measured polarization value at the peak is slightly, about 2%, lower than the calculated value (99.8%). The main reason of the low P_c could be the effect of the radiation from other source, for example edge radiation. Additional experiments were carried out in order to investigate the properties of this radiation. At maximum gap undulator magnetic field is small enough and doesn't affect the beam trajectory. Therefore, the measurements of polarization properties and intensity of non-undulator radiation were performed at gap value 200 mm. They show that average value of non-undulator radiation (NUR) is two orders lower than the fundamental peak intensity, see Fig. 6a. Non-undulator radiation is nearly linearly polarized with almost constant normalized Stokes parameters *(0.67, 0.40, 0.01)* at each measured points.

The degree of "pure" undulator radiation (UR) was estimated for all energy region with taking into account measured polarization properties and $Q = I_{NUR}/(I_{NUR} + I_{UR})$ ratio, where $(I_{NUR} + I_{UR})$ is the overall intensity for minimum gap (30mm) and I_{NUR} is that for maximum gap (200mm). It is important to note that in the analysis of "pure" UR polarization properties the undulator and non-undulator were considered as incoherent radiation sources. At first, Stokes parameters of the UR were calculated according to the following formulae:

$$(1-Q)\begin{pmatrix} S_1/S_0 \\ S_2/S_0 \\ S_3/S_0 \end{pmatrix}_{UR} = \begin{pmatrix} S_1/S_0 \\ S_2/S_0 \\ S_3/S_0 \end{pmatrix}_{UR+NUR} - Q\begin{pmatrix} S_1/S_0 \\ S_2/S_0 \\ S_3/S_0 \end{pmatrix}_{NUR} .$$

After that polarization properties of "pure" UR were found according to Eq. .

As an example, the radiation parameters of the "pure" UR at the fundamental peak are shown at the third column of the Table 2. Using experimentally measured Q value degree of circularly polarization of the UR was found to be higher than measured P_c value in all photon energy region, as shown in Fig. 6b. Obviously, influence of the NUR is much stronger for energy region above and below the peak. The degree of polarization for "pure" undulator radiation it still slightly reduced comparing with the calculation. This difference could be caused by the imperfection of Samson's model, which is usually applied in VUV and soft X-ray regions. Since the grating is treated simply as a mirror in the calculation, these effects may be caused by the diffraction at a grating. Another reasons of difference in measured and simulated results could be the misalignment of the beamline, small deviation of the beam orbit from the designed one or inaccuracy of measurement system. However, one can see from the Table 2, that the influence of these errors to the degree of circular polarization is very small.

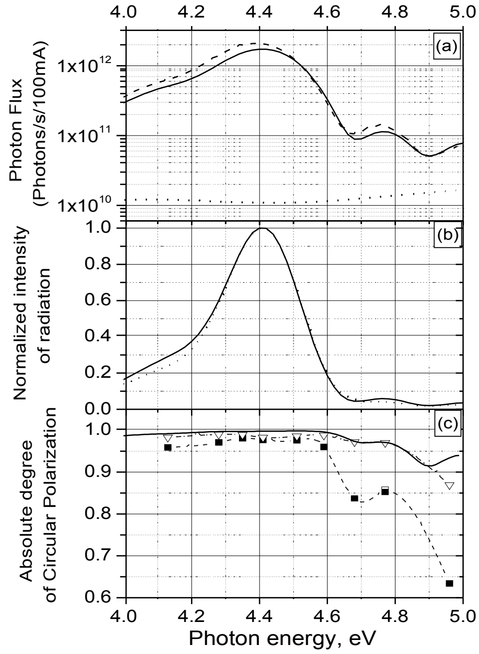

Fig. 6. *Intensity of radiation and the degree of circular polarization. (a) measured photon flux. Solid line - gap 30 mm and phase 25 mm, dash line - gap 30 mm and phase –25 mm, dot line - gap 200 mm; (b) normalized intensity of undulator radiation at gap 30 mm and phase 25 mm (solid line), in comparison with the calculation (dot line); (c) degree of circular polarization. Solid line corresponds to the calculated P_c, black squares (■) show measured P_c, and open triangles (∇) show P_c of "pure" undulator radiation*

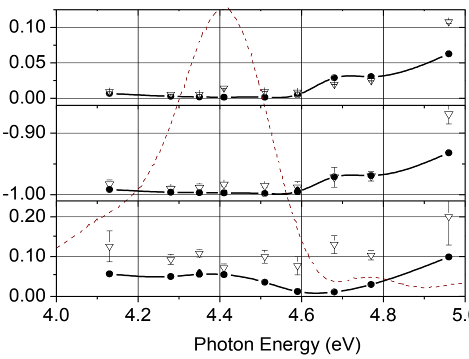

Fig. 7. *Calculated and estimated degrees of polarizations. black squares (■) are measured values of the radiation polarization properties and open triangles (∇) are estimated values of "pure" undulator radiation characteristics. P_c and P_L are degree of circularly and linearly polarization. P_U is the degree of unpolarized light. Dash line indicates the position of fundamental peak*

The results of comparison of all polarization properties of "pure" undulator radiation estimation and calculation are shown at Fig. 7. One can see, that the degrees of circularly polarization and unpolarized light are in good agreement, the only noticeable difference is in degree of linear polarization. In the described above estimation of "pure" UR polarization properties the interference effect of undulator and non-undulator radiation was not taken into account. The difference between "pure" radiation properties and calculations may be caused by such interference. To investigate this problem, additional calculations were performed with the including of the effect of radiation from bending source by the new complex of computer codes SMELRAD (SiMulation of ELectromagnetic RADiation) [13]. These codes employ the same to the codes for wiggler radiation [12] approach. However, the electron tracking can be performed in the total field from many sources with arbitrary magnetic field, for example in the fields of two bending magnets and undulator. In this case calculations include interference effects from different radiation sources, for example undulator field and fringe field at bending magnets. Simulation of edge and wiggler radiation characteristics was performed in experimentally measured magnetic fields with taking into account electron beam emittance. Results of such computation are shown at Fig. 8 together with the results of measurements. The better agreement between both results is obtained compared with the calculations of just undulator radiation properties. However, the agreement is not so good, which means that some other sources of radiation, like quadrupole radiation, should be taken into account.

Intensity of radiation and its polarization properties were also measured at opposite helicity of helical mode, i.e. side arrays shift d is equal to $-\lambda_u/4$. The results were in good agreement with the measurements at $d=\lambda_u/4$. The small difference in radiation intensity, see Fig. 7a, was probably caused by deviations in electrons orbit. Absolute value of the degree of polarization at fundamental peak of the radiation intensity was the same for both measurements.

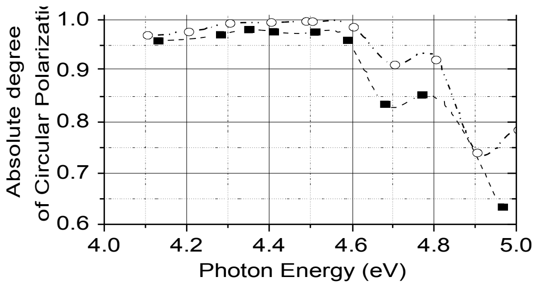

Fig. 8. *Measured (black square ■) and calculated with the including of interference effects of undulator and edge radiation (open circle ○) degree of circular polarization*

CONCLUSION

Linear / helical multimode undulator at HiSOR successfully generates radiation with almost the same performance to the designed values. Stokes parameters were experimentally determined for helical mode of multimode undulator at minimum gap for 4-5 eV energy region by performing of polarization measurements using IR-UV polarimeter. Measurements show the high degree of circular polarization. The experimental results were compared with the numerical calculations. The main reason of difference between them is in the influence of non-undulator radiation, such as bending or edge. Regardless of the fact that the intensity of such radiation is small compared to the intensity of undulator radiation, it can changes the polarization state of the light, especially in the regions above and below of the fundamental peak.

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