J. Synchrotron Rad. (1998). **5**, 462–464

A practically zero horizontal magnetic field in a planar undulator used in the Tristan Super Light Facility

Shigeru Yamamoto,[a*] Kimichika Tsuchiya,[a] Tatsuro Shioya,[a] Daizo Amano[b] and Hiroshi Sugiyama[a]

[a]Photon Factory, High Energy Accelerator Research Organization, Oho, Tsukuba, Ibaraki 305, Japan, and [b]Laboratory for Quantum Equipment Technology, Sumitomo Heavy Industries, Yato, Tanashi, Tokyo 188, Japan. E-mail: shigeru@kekvax.kek.jp

(*Received 4 August 1997; accepted 6 November 1997*)

The Tristan Main Ring (MR) at KEK (High Energy Accelerator Research Organization) has been used as a third-generation synchrotron radiation ring with an undulator installed in the MR as a third-generation light source. The magnetic field irregularities of the undulator were examined precisely. Measurement of the magnetic field after synchrotron radiation experiments showed that the magnetic irregularities in both the horizontal and vertical directions are negligibly small. This result suggests that our previous estimates of emittance, made using the measured undulator spectrum, should correctly represent the properties of the electron beam in the MR.

Keywords: undulators; undulator field; spectrum measurements; large accelerators as light sources.

1. Introduction

During the last three and a half months of 1995, we performed some synchrotron radiation experiments using the Tristan Main Ring (MR) at KEK (High Energy Accelerator Research Organization) as a third-generation light source (KEK, 1993). For the characterization of X-rays from an undulator (XU#MR0), having a period length (λ_u) of 4.5 cm and number of periods (N) of 120, we performed spectrum measurements in terms of the photon-flux density, and made an estimation of the electron-beam emittance, such that a natural emittance (ε_0) of 14 nm and an emittance coupling (κ) of 0.015 were achieved (Yamamoto *et al.*, 1997). A series of research papers using the high brilliance of this source have been published (see *e.g.* Photon Factory, 1998). Nevertheless, we have found that the observed photon-flux density had half the expected value. The design parameters of the electron beam were ε_0 = 5 nm and κ = 0.02 (Kamada *et al.*, 1995). From the viewpoint of undulator technology, it is important to understand this discrepancy. In the present paper we try to elucidate this by examining the magnetic field of the XU#MR0 undulator precisely.

2. Emittance estimation based on the measured spectrum

A spectrum measurement of the radiation from the undulator was made during the 10 GeV and 10 mA operation of the MR. Its lattice was specially modified as a third-generation synchrotron radiation source (Kamada *et al.*, 1995). The XU#MR0 undulator was operated with a deflection parameter (K) of 1.09 (a first harmonic energy of 13.1 keV) for the spectrum measurement; its basic parameters are given in Table 1. The angular photon-flux density was measured by introducing X-rays to a PIN photodiode detector through an aluminium absorber and an xy slit (with an aperture of 0.2 × 0.2 mm at a point 95 m from the undulator), which were placed after the Si 400 double-crystal monochromator. Its first crystal was cooled by liquid nitrogen (Sugiyama *et al.*, 1998). The effect of ambient magnetic fields in the MR tunnel was corrected using long coils set along the total length of the XU#MR0 (Yamamoto *et al.*, 1997).

In several synchrotron radiation facilities, methods for emittance measurements have been successfully developed (Tarazona & Elleaume, 1995; Cai *et al.*, 1996). In our previous study (Yamamoto *et al.*, 1997), we obtained the values ε_0 = 14 nm and κ = 0.015 based on the measured values of the flux density ($\mathcal{D}_1$) and

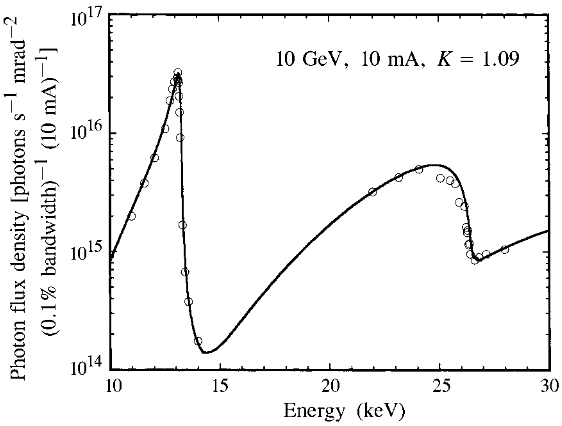

Figure 1
On-axis spectra (photon-flux density) of the radiation from the XU#MR0, measured (circles) and calculated (solid curve) using the electron-beam emittance, which was estimated based on this measurement (this figure was reproduced from Yamamoto *et al.*, 1997). The XU#MR0 was used at K = 1.09 (the first harmonic energy is 13.1 keV) when the MR was operated at 10 GeV and 10 mA. This calculation was made with a natural emittance (ε_0) of 14 nm, and an emittance coupling (κ) of 0.015; an energy spread of 1.13 × 10^{-3} and the Twiss parameters of the electron beam were also taken into account.

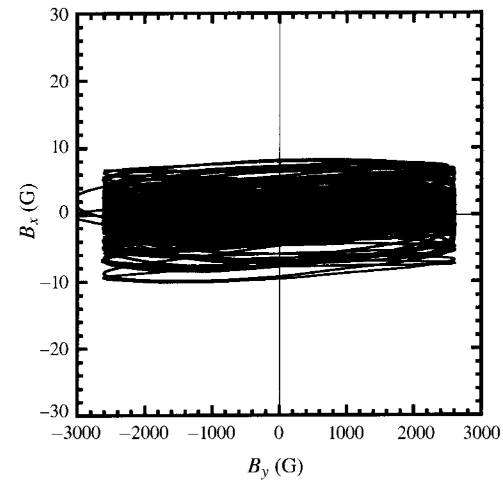

Figure 2
Horizontal (B_x) and vertical (B_y) magnetic field in the XU#MR0 at K = 1.09 (or gap = 30 mm). The variation in both components along the z axis is plotted on the xy plane.

Table 1
Parameters of the XU#MR0.

Magnetic structure	Pure configuration
Magnetic material	NdFeB (B_r = 12.8 kG, iH_c = 17 kOe)
Period length	λ_u = 4.5 cm
Number of periods	120 (= 3 × 40/unit undulator)
Magnet length	5.4 m (= 3 × 1.8 m/unit undulator)
Maximum peak field	B = 2.64 kG
Maximum K	K = 1.11
Magnet gap range	3–50 cm
Aperture	2.4 cm

bandwidth ($\Delta\omega/\omega_1$) of the first harmonic and the ratio of the flux density of the second harmonic to the first ($\mathcal{D}_2/\mathcal{D}_1$) using different dependences of these three quantities on ε_0 and κ. One of these three quantities was used for a redundancy check. The different dependences of these quantities were obtained by calculating the spectra for the various sets of ε_0 and κ with the analytical formulae of the undulator radiation (*e.g.* Kitamura, 1980). In this process we took into account the effects of the emittance, the energy spread (1.13×10^{-3}) and the Twiss parameters of the electron beam in the MR, under the assumption of an ideal magnetic field in the undulator.

The good agreement (Fig. 1) between the measured (circles) and the calculated (solid curve) spectra suggests that the above result of the emittance estimation was appropriate. For this calculation, the effects of the emittance, the energy spread and the Twiss parameters were also taken into account. In order to reach this conclusion, however, we need to show that there are no or only negligibly small irregularities in the magnetic field of the undulator, since we did not have any information on the horizontal magnetic component when we constructed it.

3. Horizontal magnetic field and its effects on the spectrum

After the synchrotron radiation experiments in the MR, we measured the magnetic field of the XU#MR0 again, in order to investigate any magnetic irregularities in the horizontal direction as well as in the vertical direction. For this purpose we used a magnetic sensor which has two Hall probes for both the horizontal (B_x) and vertical (B_y) fields. The temperature of these probes is stabilized at 303 ± 0.01 K in a micro-oven, as used in the previous study (Yamamoto *et al.*, 1995).

Fig. 2 shows the result of a measurement made at $B_{y,0}$ (the vertical peak field) of 2600 G (1 G ≡ 10^{-4} T), at which our spectrum measurements and several synchrotron radiation experiments were performed. The accuracy of the horizontal-field measurement was better than 0.2 G at B_y = 3000 G. From the

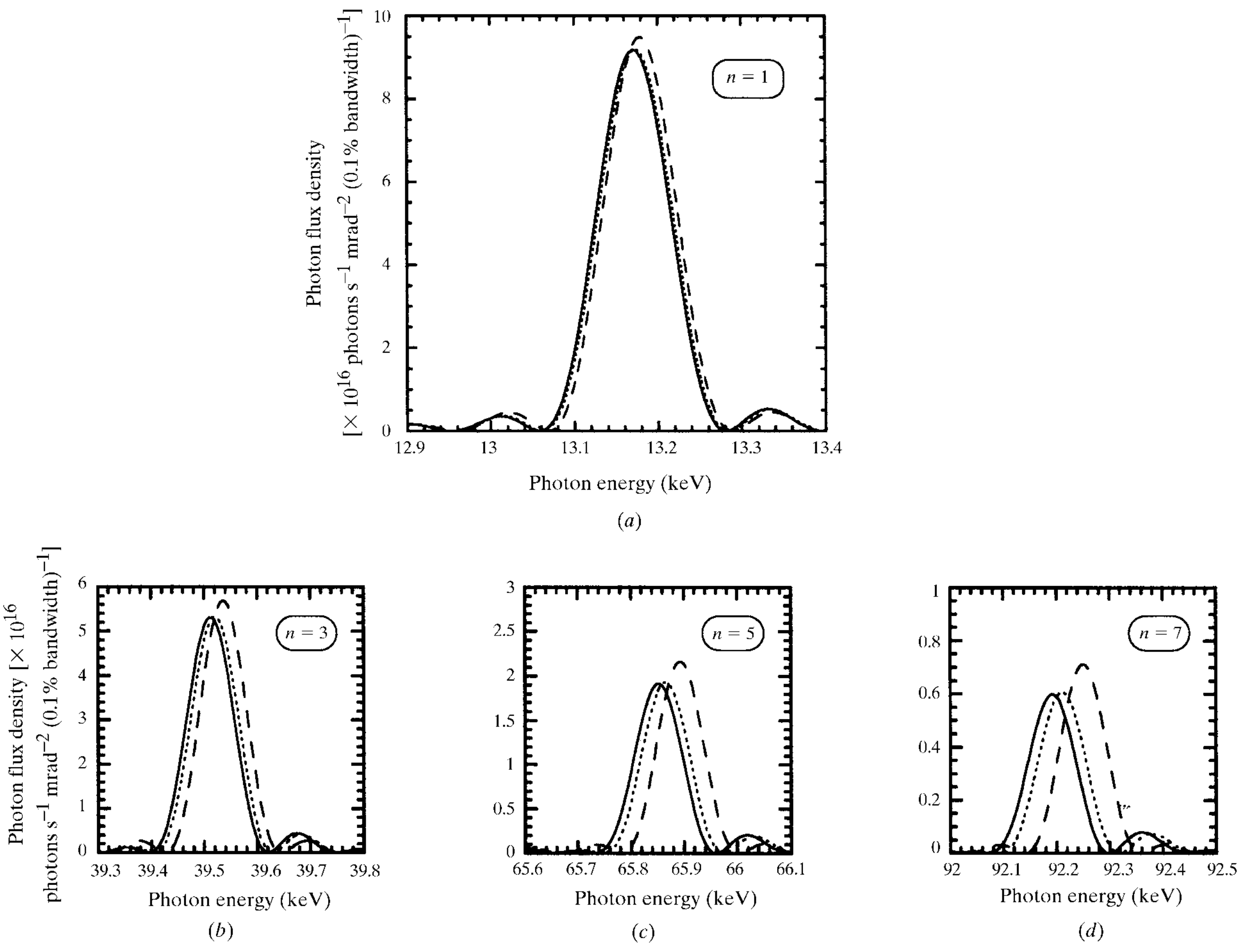

Figure 3
(*a*) Calculated on-axis spectrum (photon-flux density) obtained by a Fourier transform of the measured magnetic data on the XU#MR0 (K = 1.09, λ_u = 4.5 cm and N = 120) for the first harmonic in the case without any electron beam emittance. The present case (solid curve) is compared with a completely ideal case (dashed curve) without errors in both the vertical and horizontal fields, and also with a case without horizontal errors ($B_x \equiv 0$; dotted curve). (*b*) Calculated spectrum for the third harmonic obtained in a same way as in (*a*); (*c*) fifth harmonic and (*d*) seventh harmonic.

present measurement we found that (i) although the horizontal field was not zero, its values were comparable to the root-mean-square error of the vertical field ($\Delta B_x = \pm 5$ G), and (ii) the vertical field remained unchanged after its construction during the experimental period (the field fluctuation at each pole was well suppressed to ± 5 G as a root-mean-square value).

In order to investigate the significance of the non-zero horizontal magnetic field as well as the fluctuation in the vertical field, we obtained spectra of the radiation from the undulator by performing a Fourier transform using the measured magnetic data. The results are shown in Fig. 3(*a*) for the first harmonic, which was used in the spectrum measurement; the calculation was made for the case without any electron-beam emittance, and the so-called far-field approximation gave the same result as the near-field calculation owing to the length of the beamline (nearly 100 m). This present method also gave the same result as the analytical calculation for the case of an ideal magnetic field. In Fig. 3(*a*) the present case (solid curve) is compared with the completely ideal case (dashed curve) without errors in both the vertical and horizontal fields, and also to the case without the horizontal errors (dotted curve). Degradation of the photon flux density due to magnetic irregularities in the present case was less than 3% at the first harmonic. It should be noted that the effect of the horizontal magnetic irregularities is negligibly small, as can be seen from a comparison between the cases with and without horizontal errors. The degradation of the photon-flux density for several higher harmonics is still kept very small, as shown in Figs. 3(*b*) (third), 3(*c*) (fifth) and 3(*d*) (seventh harmonic).

4. Conclusions

We found that the present magnetic data reveal very small errors in the horizontal component of the magnetic field as well as in the vertical component, and that their effect on the radiation spectra is negligibly small. This fact may justify the assumption that the undulator has an ideal magnetic field and hence we can estimate the emittance (ε_0 = 14 nm and κ = 0.015) from the measured spectrum. Furthermore, the good agreement between the spectrum based on this estimation and the measured one suggests that our estimation should represent the status of the electron beam in the MR correctly, when the synchrotron radiation experiments were performed.

The authors express their sincere thanks to Professor M. Ando for his help and to the staff of the Tristan accelerator group for their collaboration.

References

Cai, Z., Dejus, R. J., Den Hartog, P., Feng, Y., Gluskin, E., Haeffner, D., Ilinski, P., Lai, B., Legnini, D., Moog, E. R., Shastri, S., Trakhtenberg, E., Vasserman, I. & Yun, W. (1996). *Rev. Sci. Instrum.* **67**(9), CD-ROM.

Kamada, S., Fukuma, H., Ogata, A., Isawa, M., Nakamura, N., Sakanaka, S., Tobiyama, M., Ohmi, K., Kanazawa, K., Kubo, T., Egawa, K., Mitsuhashi, T., Mimashi, T., Kobayashi, M. & Katsura, T. (1995). *Rev. Sci. Instrum.* **66**, 1913–1915.

KEK (1993). *The Tristan Super Light Facility; Conceptual Design Report 1992.* KEK Progress Report No. 92–1. KEK, Tsukuba, Japan.

Kitamura, H. (1980). *Jpn. J. Appl. Phys.* **19**, L185-L188.

Photon Factory (1998). *Project §A.* In *Photon Factory Activity Report No. 14*. In preparation. Photon Factory, Tsukuba, Japan.

Sugiyama, H., Zhang, X., Higashi, Y., Arakawa, E. & Ando, M. (1998). In preparation.

Tarazona, E. & Elleaume, P. (1995). *Rev. Sci. Instrum.* **66**, 1974–1977.

Yamamoto, S., Shioya, T., Kitamura, H. & Tsuchiya, K. (1995). *Rev. Sci. Instrum.* **66**, 1996–1998.

Yamamoto, S., Sugiyama, H., Tsuchiya, K. & Shioya, T. (1997). *J. Synchrotron Rad.* **4**, 54–59.