Construction of an in-vacuum type undulator for production of undulator x rays in the 5–25 keV region

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A new 179-pole undulator with magnetic period of 4 cm for production of brilliant and quasimonochromatic hard x rays has been completed and installed in the TRISTAN Accumulation Ring (AR) in KEK, National Laboratory for High Energy Physics. The aperture of the undulator for the circulating electron can be flexibly changed to satisfy the operational requirements of AR, since the undulator magnets are encased in the vacuum chamber of the undulator. When it is operated at the magnet gap of 20 mm with 6.5-GeV operation of AR, intense 14.4-keV radiation for Mössbauer experiments is successfully obtained as the third harmonic of the undulator radiation.

I. INTRODUCTION

If undulator radiation is obtained in a hard x-ray region (5–25 keV), it should be a very important probe in many research fields of sciences because of its high brilliance, quasimonochromaticity and tunability. For generation of the undulator radiation in the higher energy region the higher electron beam energy and the shorter period of the undulator field are suitable as seen from the relation (on axis) between photon energy E_n of the nth harmonic and magnetic period λ_u.

$$E_n(\text{keV}) = \frac{2.48\times 10^{-7} n\gamma^2}{\lambda_u(\text{cm})}\left[1+\frac{K^2}{2}\right]^{-1}. \quad (1)$$

Here γ is the relativistic energy of the electron beam. K is a deflection parameter characterizing the radiation from an undulator, which is given by

$$K = 9.34\times 10^{-5} B_0(\text{G})\lambda_u(\text{cm}), \quad (2)$$

where B_0 is a maximum of the magnetic field intensity of the undulator.

The TRISTAN Accumulation Ring (AR) at KEK, National laboratory for High Energy Physics, is useful for the above purpose because of its high beam energy of 6.5 GeV ($\gamma = 12720$). From Eq. (1) in case of AR we find that we can have the undulator x rays in the 5–25 keV region as the lower harmonics ($n = 1$–5), if we can adopt a short period of $\lambda_u = 2$–6 cm: e.g., the 14.4-keV radiation as the third harmonic at $K = 1.47$ with $\lambda_u = 4$ cm. However, such short periods require a narrow magnet gap of the undulator of 1–2 cm for the generation of enough field strength, and eventually result in a narrow aperture for the circulating beam. In usual undulators the aperture is fixed at the size smaller than that of the minimum gap, since the field is applied to the beam through a wall of a vacuum duct. Therefore, the construction of such undulators is nearly impossible, not only in a parasitic use with high energy experiments as in AR but in a dedicated use of the storage ring, since an allowed aperture is as small as 0.5–1.5 cm due to thickness of the duct wall.

If undulator magnets can be brought into a ring vacuum system, the degrees of freedom to operate such an undulator (hereafter designated as "in-vacuum" type undulator) and the ring would be largely enhanced, and the above problem is completely resolved. This is because the undulator aperture can be changed to satisfy the requirements for the storage-ring operation; (1) when the undulator radiation is used, the desired field strength can be obtained by closing the magnet gap, and (2) when a wide aperture is required, it is obtained by opening the gap.

In this paper we describe construction of a novel undulator of in-vacuum type. The undulator, named U#NE3, was constructed for a beamline designated as BL-NE3,[1] in which Mössbauer experiments and interface/surface experiments have been designed as primary subjects. A result of the spectrum measurements of the undulator x rays is also reported.

II. STRUCTURE OF AN IN-VACUUM UNDULATOR U#NE3

When we designed U#NE3, we selected the value of 4 cm as λ_u, on the bases of high brilliance and wide energy range (5–25 keV) of the radiation, which is available when $\lambda_u = 4$ cm. The calculated spectra with $\lambda_u = 4$ cm are compared with those with $\lambda_u = 2.4$ and 6 cm in Fig. 1. The calculation was made with a condition of the 6.5 GeV and low-emittance operation of AR (horizontal and vertical emittances of the electron beam are: $\epsilon_x = 1.63\times 10^{-7}$ m·rad and $\epsilon_y = 1.63\times 10^{-9}$ m·rad). Figure 1 also shows that the 4-cm period is suitable for generation of the radiation tuned in on 14.4 keV, which is the most popular in the Mössbauer experiments. Furthermore, from a view point of the reduction of heat load to the beamline components, we found that $\lambda_u = 4$ cm is preferable. For generation of the 14.4-keV radiation with the third harmonic, the power density, P_d for $\lambda_u = 4$ cm amounts to 1 kW/mrad^2, when 50 mA operation of AR is assumed. This is much lower than in other cases; $P_d(\lambda_u = 2.4 \text{ cm}) \approx 4$

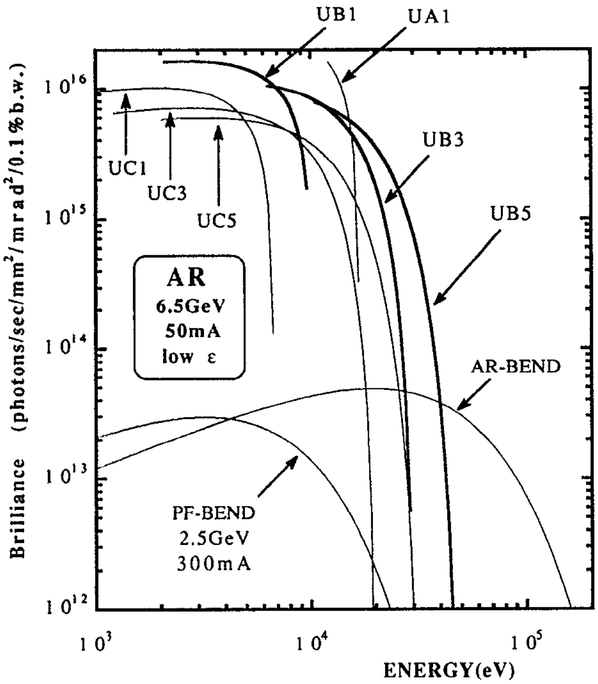

FIG. 1. Calculated spectra of radiation from U#NE3. UA, UB, and UC correspond to the cases of $\lambda_u = 2.4$, 4, and 6 cm, respectively. Calculation is made in the case of 6.5-GeV low-emittance operation of AR with 50 mA: $\epsilon_x = 1.63\times10^{-7}$ m·rad and $\epsilon_y = 1.63\times10^{-9}$ m·rad. A number after UA (or UB or UC) denotes the order of harmonic. Each curve denotes the locus of the peak position of each harmonic with K value. Spectra of bending radiations of AR and the 2.5-GeV Photon Factory Ring are shown for comparison.

kW/mrad^2 with the first harmonic, and $P_d(\lambda_u = 6\text{ cm}) \approx 9$ kW/mrad^2 with the seventh harmonic with the same condition of AR.

U#NE3 consists of a pair of permanent-magnet arrays, a vacuum chamber containing the arrays, and a mechanical frame which controls the magnet gap through bellows couplings, as shown in Fig. 2. The basic parameters of U#NE3 are listed in Table I.

The magnets are arranged in the pure Halbach type configuration:[2] $\lambda_u = 4$ cm, a number of periods $N = 90$. As magnet material, we have selected Nd–Fe–B alloy with the remanent field of $B_r = 12$ kG and the coercivity of $iH_c = 21$ kOe (NEOMAX33SH manufactured by Sumitomo Special Metals Co. Ltd.), because of its magnetic performance and endurance against high temperatures for heating evacuation. Magnet blocks made of the above porous material are plated with Ni (25-μm thick) for a vacuum sealing. They are embedded in a holder of stainless steel, and attached on a pair of magnet-mounting beams made of Al.

The above components of the magnet system are enclosed in a large vacuum chamber made of stainless steel, whose inside surface is electrolytically polished; the size of the chamber is 60 cm (inner diameter) × 410 cm (length). Total surface area of the inside of the chamber amounts to about 30×10^4 cm^2 including the surface area of the magnets of 3.7×10^4 cm^2. The vacuum chamber is evacuated with nonevaporable getter (NEG) pumps having a pumping speed of 3600 ℓ/s and four sputter ion pumps (SIP) having a total speed of 880 ℓ/s. The magnet gap is controlled by a translation system composed of precise ball screws and linear guides. Translation of this system is transmitted to the magnet arrays through linear motion feedthroughs using bellows coupling. The available region of the magnet gap is ranging from 50 to 10 mm. With the present vacuum-sealing method using metal plating, the aperture of the undulator is almost equal to the magnet gap. This point is another advantage of the in-vacuum undulator using metal-plated magnets, and is especially important when the gap is closed (e.g., when gap = 10 mm). The magnetic field of U#NE3 ranges from 0.36 G to 8.2 kG as a function of the gap; in terms of the deflection parameter, it ranges from 0.13 to 3.1.

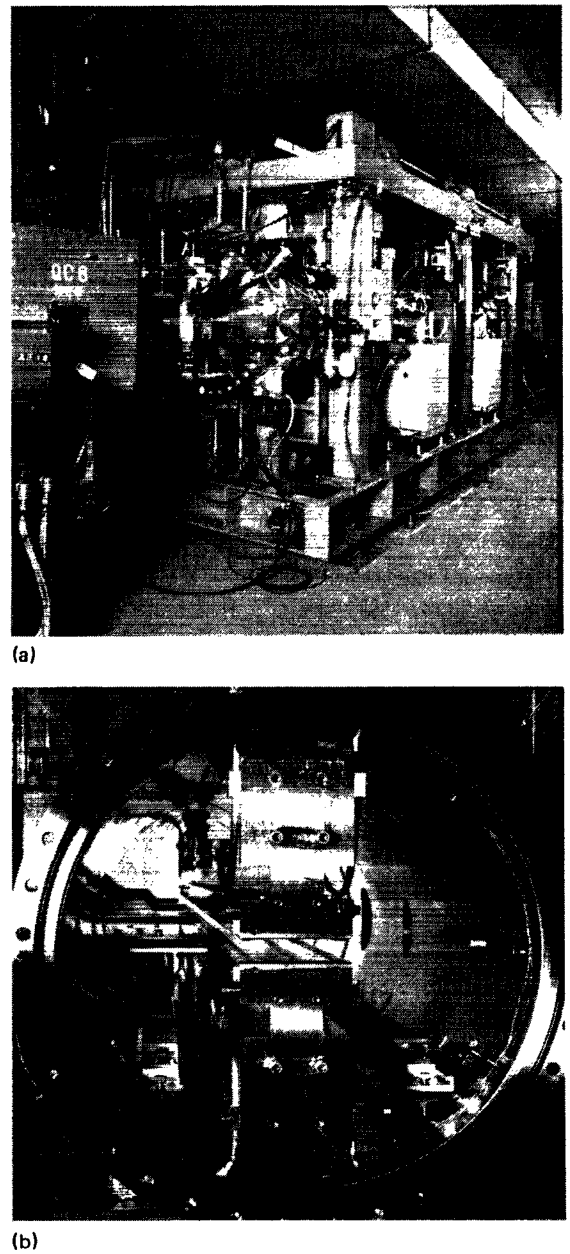

FIG. 2. Photographs of U#NE3: (a) an external view after the installation into AR, and (b) an inside view.

In the vacuum chamber of U#NE3, there are many

TABLE I. Parameters of U#NE3.

Period length	4 cm
Number of poles	179 + 2
Magnet length	360 cm
K	0.13–3.1
B_0	0.36–8.2 kG
Minimum gap	1.0 cm
Maximum gap	5.0 cm
Magnet structure	Pure
Magnet material	NdFeB (Ni plated)

discontinuities in the wall current paths: narrow but many openings (about 300 μm wide) between individual magnets in each of the magnet arrays and large ones (about 120 mm wide) between the end of the magnet array and the Q duct of AR. These discontinuities might result in heating of the magnets and vacuum failure, as a result of the coupling of radio-frequency power between the electron beam and the wall current paths (or as a result of parasitic mode loss). In the present case, the effect of the parasitic mode loss should be very serious, if the discontinuities are left without suitable treatments.[3] In order to keep the wall current path continuous, first we put in laminar (100-μm thick) sheets of stainless steel on both opposed faces of the magnet arrays. Second, we devised a contactor composed of many strips (100-μm thick × 4-mm wide) of stainless steel, which flexibly connects the end of the laminar sheet to the Q duct of AR.[4]

III. ACHIEVEMENT OF ULTRAHIGH VACUUM AND PREVENTION OF DEMAGNETIZATION DURING A BAKEOUT PROCESS FOR EVACUATION

In order to achieve ultrahigh vacuum in the chamber which is required for the stable operation of AR and to prevent deterioration of the undulator field during a bakeout process for evacuation, here we found that the following treatments are useful.[4,5] They are: (1) 200-°C baking (36 h) of the plated blocks of the magnets before magnetization and (2) 125-°C baking (48 h) of the magnetized blocks of the magnets arranged in the pure configuration. Both treatments were made in vacuum. The details of these treatments are given elsewhere.[4,5]

The 200-°C baking is the treatment for degassing molecules (mainly H_2O) adsorbed on the surface of the magnets during the wet-type plating process. The 125-°C baking is made for "magnetic stabilization." The magnetic deterioration is inevitable when the magnets are heated.[6] Even though the present magnets are highly durable against high temperature, the reduction of B_0 amounts to 2% of the value at 25 °C with the first 125-°C baking when $B_0 = 4$ kG.[4] However, the reduction is negligibly small after the second baking at the same or lower temperature.[4] Thus, the deterioration at high temperature for ultrahigh vacuum can be avoided by heating the magnets in advance at the same or higher temperature. In the present construction, we made the magnetic stabilization at 125 °C and the commissioning of vacuum at 115 °C, as described below.

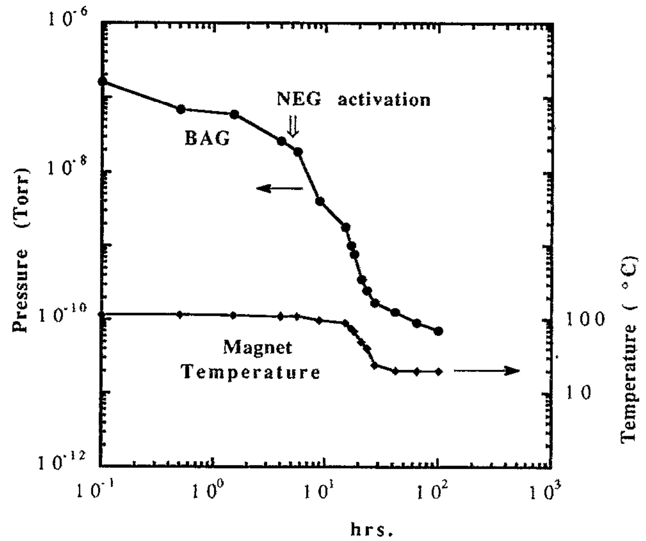

FIG. 3. Evacuation curve of U#NE3. NEG stands for nonevaporable getter pumps, and BAG does for a Bayard–Alpert gauge for pressure measurements. The temperature of the magnets is also shown.

Figure 3 shows the evacuation curve of U#NE3 as a relation between pressure in the chamber and pumping time. The vacuum chamber of U#NE3 which enclosed the magnets after the above treatments, was evacuated by SIP and NEG pumps after the bakeout at 114.5±0.5 °C for 48 h. The ultimate pressure as low as 7×10^{-11} Torr was obtained with the above 200-°C baking. The usefulness of the 200-°C baking was confirmed by bench test using sample magnets,[4] although the case without the 200-°C baking was not examined in the real U#NE3. It is noted that the effect of the 200-°C baking survived a long exposure to the air for 3 months.

Figure 4 shows the effect of the 125-°C baking for magnetic stabilization. The quality of the undulator field in U#NE3 is shown in Fig. 4 in terms of the electron orbit in U#NE3 when B_0 is set at 4 kG for the 14.4-keV radiation. This is because the field quality is more obvious when expressed as the electron orbit than expressed as the magnetic field itself. A comparison between the orbits before and after the baking for the vacuum commissioning at 115 °C, indicates that any significant deterioration of the undulator field did not occur during the commissioning.

The electron orbits shown in Fig. 4 are calculated on the basis of precise measurement of the magnetic field in U#NE3, using Hall generator. For this measurement, we devised a holder for the Hall generator which meets the narrow gap of about 10 mm. This holding apparatus is a kind of a microoven of Cu equipped with a thermister-type thermometer and heaters, and is used to reduce errors in the generator's output due to temperature variations during field measurement. By combining this apparatus with an appropriate temperature controller, we can obtain an accuracy of temperature higher than 0.01 °C, and obtain finally a relative accuracy of the magnetic field of 1×10^{-5}.

Optimization of the undulator field was made by basically the same method as used in the previous work.[7] As a

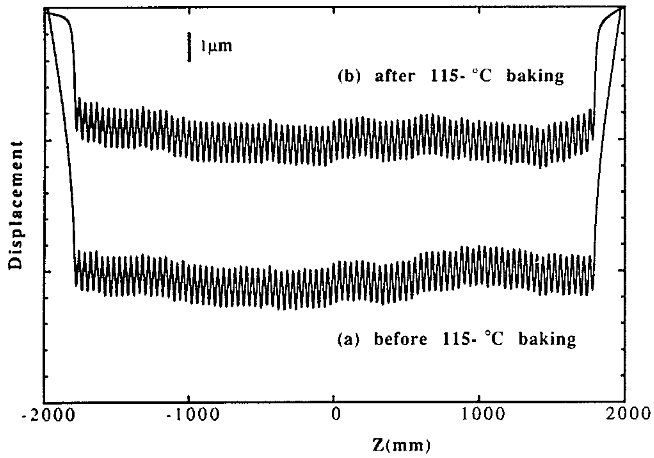

FIG. 4. Electron orbits (a) before and (b) after the 115-°C baking for ultrahigh vacuum. The deterioration of the undulator field which is expressed as a variation in the orbits is very small. Vertical bar represents 1 μm of displacement.

criterion in this process, we used the following condition about a deflection angle θ_{def} of the envelope of the electron orbit to obtain a good transverse coherence of the radiation: $\theta_{def} \ll \sigma_{r'} = \sqrt{\lambda/N\lambda_u}$. Here $\sigma_{r'}$ is a divergence angle of the undulator radiation having a wave length, λ. In the present case we adopted $\lambda = 0.860$ A and $\sigma_{r'} = 5.5\times10^{-6}$ rad, since the Mössbauer experiments using this radiation are the most important subject in BL-NE3.

IV. SPECTRUM MEASUREMENTS OF UNDULATOR X RAYS

The radiation is extracted through water-cooled graphite absorbers for protection of beamline components and Be windows for vacuum isolation between the beamline and AR. The detailed description of BL-NE3 will be given elsewhere.[1] The present characterization was made on axis by a Si(111)-double-crystal monochromator with a NaI scintillation counter at the AR's operational condition of 6.5 GeV and 0.3 mA with low-emittance optics. A result is shown in Fig. 5 in the case of $K = 1.47$ where the 14.4-keV radiation is obtained as the third harmonic. The observed spectrum in Fig. 5 corresponds to angular flux density since the radiation was strictly limited using a four-dimensional slit with a small aperture (0.02×0.02 mm^2) placed before the NaI counter. Figure 5 also shows a theoretical calculation made with the parameters used in Fig. 1 together with energy spread of 1.15×10^{-3} of the electron beam. In Fig. 5 they are compared in an arbitrary scale so that peaks of the second harmonics for both observation and calculation have the same height. Although agreement between the observation and the calculation is remarkable in the energy region above 5 keV, discrepancy in the region below 5 keV is rather large. We think that this should be responsible for absorption by impurity components (less than 1%) in the material of the graphite absorbers and the Be windows. The absorption of graphite (0.2-mm thick totally) and Be (0.7-mm thick totally) is taken into account together with the effect of the air (150-mm thick) between the monochromator and the NaI counter.

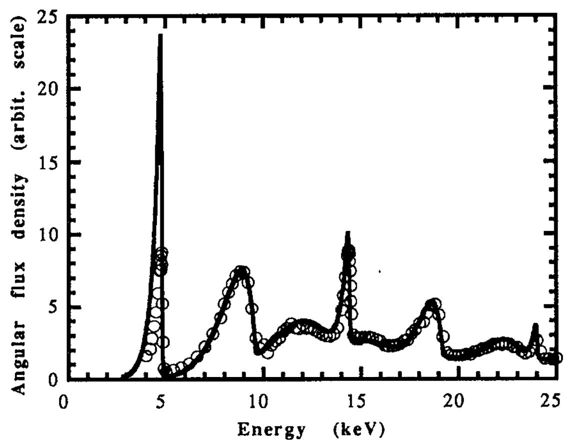

FIG. 5. A result of on-axis observation of the undulator x rays from U#NE3. Effects of absorption of the graphite-absorber (0.2-mm thick), Be window (0.7-mm thick), and the air (150-mm thick) on an x-ray path are taken into account for correction for the measured values. A calculated spectrum (solid curve) is compared with the observation (circles); it was made with the same condition as in Fig. 1. An effect of energy spread of 1.15×10^{-3} of the electron beam was also considered.

Utilization of the 14.4-keV radiation produced by U#NE3 has been started at BL-NE3 for the Mössbauer experiments as the present most important subject at a usual condition of 6.5 GeV and 20–30 mA. We are convinced that with this new experimental station many interesting experiments become possible which had to be postponed due to lack of intensity.

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