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DEVELOPMENT OF VERY SHORT PERIOD UNDULATORS*

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Abstract

We are exploring a novel method to fabricate undulator magnets having very short periods. Two types of magnet plates 100mm and 152mm long with a 4-mm period length have been successfully fabricated. A method connecting these magnet plates has also been successfully developed to fabricate longer undulator magnets. Prototype undulators based on the technology have been constructed. Magnetic field characterization based on the measured field show that the quality of the undulator field of these magnet plates is satisfactory. A spectrum calculation shows that the fundamental radiation emitted from the electrons in this field is quite useful in spectrum quality as compared to that for the ideal field.

INTRODUCTION

In IPAC'14 at Dresden the author presented a novel method to fabricate very short-period undulators, in which a magnetic field with a 4-mm period length was successfully transcribed into the plate-type magnets 100mm long [1-3]. This technique allows the undulator field to be one order-of-magnitude shorter than the ordinary period of several cm in a very short gap between a pair of opposing plate magnets. The 4-mm period length is selected so that 12-keV radiation could be generated with the first harmonic of this undulator using a 2.5-GeV electron energy.

The very short gap between the plate magnets should be allowed only in the in-vacuum undulator structure, which was invented at Photon Factory (PF), High Energy Accelerator Research Organization, KEK [4]. It has spread to other institutes including the third- and fourth-generation light sources [5]. This technology was utilized to realize the period length around 2cm in-vacuum Short Gap Undulators (SGU) at PF [6, 7].

In these years the author has improved the above method to achieve higher accuracy in the period length and higher strength of the field. He has also developed a connection technique to obtain longer undulator magnets in which several plate magnets are accurately connected without significant field errors at each connection point. The progress achieved after IPAC14 and the construction of prototype undulators are presented. Test experiments on light generation using the real electron beams based on two sources (one from a conventional S-band linac and the other from a laser-wake-field acceleration) are being prepared.

GENERATION OF A UNDULAOTR FIELD WITH A VERY-SHORT-PERIOD LENGTH

Fabrication of Very-short-period Undulator Magnets

In the construction of the ordinary undulators, we prepare magnet blocks which are shaped accurately (usually mounted on the non-magnetic holders) and aligned longitudinally on a pair of rigid girders. When we try to shorten the period length λ_u of the undulator, we need to reduce the size of the magnet blocks while keeping accuracy (*i.e.* the ratio of an error in block size and λ_u in this case). However, when λ_u is less than 10mm it is rather difficult to fabricate the accurate magnet blocks to maintain the above accuracy. Further the components for installation of these blocks, such as screw bolts, are too small to use.

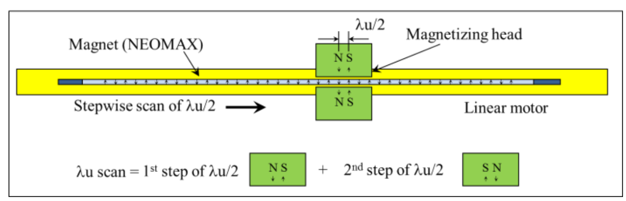

Figure 1: Perpendicular geometry is adopted in the present magnetization method.

Contrary to the ordinary method mentioned above, we have been trying to develop a completely new one to fabricate very short-period undulator magnets. Here a multi-pole magnetizing method is applied to magnetizing thin plate of the magnets. The basic idea of this method was reported elsewhere [1-3].

After trying several methods, we finally reached devising the present method which is shown in Figure 1. The plate magnet made of Nd-Fe-B type magnet material is embedded between a pair of magnetizing heads of electromagnets. It is longitudinally driven by a linear motor step-wise and magnetized with a periodic spacing by the fixed head as shown in Figure 1. The step width of the moving plate is set to a half of the period length of the magnetic field. At each step of the plate movement the pulse current applied to the head is reversed in direction to form the undulator field.

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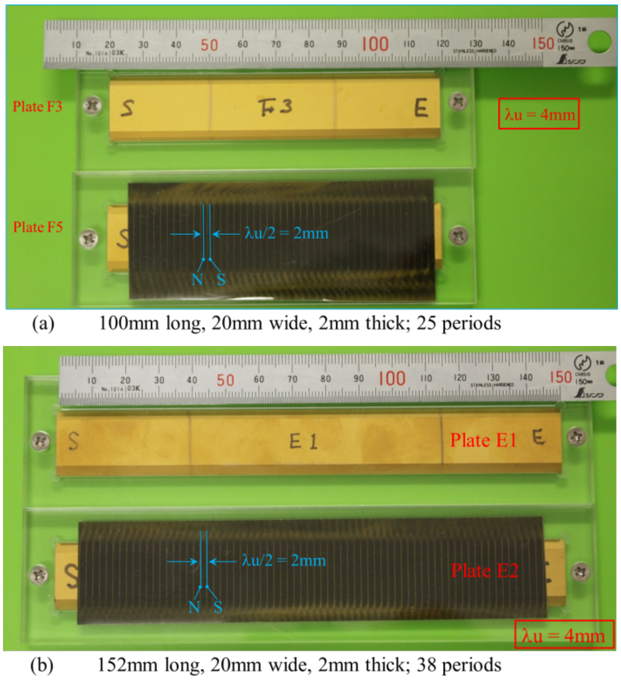

Figure 2: Magnetized plates are coated with TiN for vacuum sealing. A pair of these plates is opposed to form the undulator field; (a) plates F3 and F5 100mm long, and (b) E1 and E2 152mm long.

In Figure 1 the magnetization direction is perpendicular to the plate surface (the perpendicular case). The geometry is similar to the perpendicular magnetic recording method in a recording media.

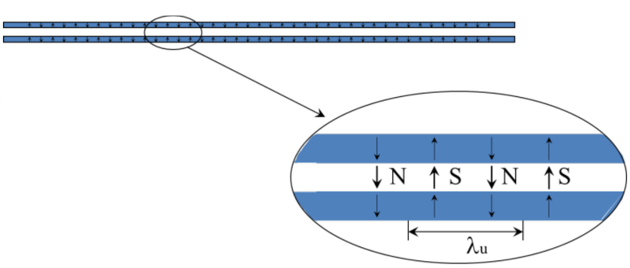

Figure 3: Formation of an undulator field in perpendicular geometry.

The other geometry (the longitudinal case) is also possible, when the current direction in one of the electromagnets is reversed with respect to that in the other magnet. In this case the magnetization is formed along the plate surface as in longitudinal magnetic recording. The magnetic field in the longitudinal case may be weaker than that in the perpendicular case. However, there is an advantage that the first field integral becomes zero if the magnetization direction is purely longitudinal. It holds true even if there are errors in the magnetization strength.

The accuracy of the period length of the plate magnetic field is mainly determined by the accuracy of the spacing of the wires in the head and of the step width of the plate movement driven by the linear motor. It is controlled by a closed loop scheme with an accuracy of 0.003mm. We also devised the magnetizing head in which tight and accurate wire spacing were achieved. Thus, the accuracy of the achieved field strength is essentially determined by the precision in the period length and of the quantity of the electric charge applied to the head at each step.

The magnetized plates having a 4-mm period length are shown in Figure 2. A pair of plate magnets 100mm long (F3 and F5) is shown in Figure 2a and another pair of E1 and E2 152mm long in Figure 2b. They are made of NEOMAX-37SH (Hitachi Metals Co. Ltd.) and coated with TiN for vacuum sealing. Here, the plate magnets are contained in a case made of an acrylic resin to isolate each other and to avoid accidents. The magnetic field pattern is seen through a magnetic viewer sheet for the plate F5 in Figure 2a and for E2 in Figure 2b. The present success of the magnetization reveals that a “monolithic” undulator magnet is now available if a periodicity of 25 for the 100mm-long plate (or 38 for 152mm-long one) is enough for the practical use of synchrotron radiation. Further the fabrication of these plate magnets is useful for reducing the size of the undulators and finally for conservation of resources, such as rare earth elements, which are major components of Nd-Fe-B magnets.

Formation and Characterization of an Undulator Field

After the magnetization, a pair of these plates is combined with faces opposing each other, and the undulator magnetic field is produced in the short gap between the plates as shown in Figure 3.

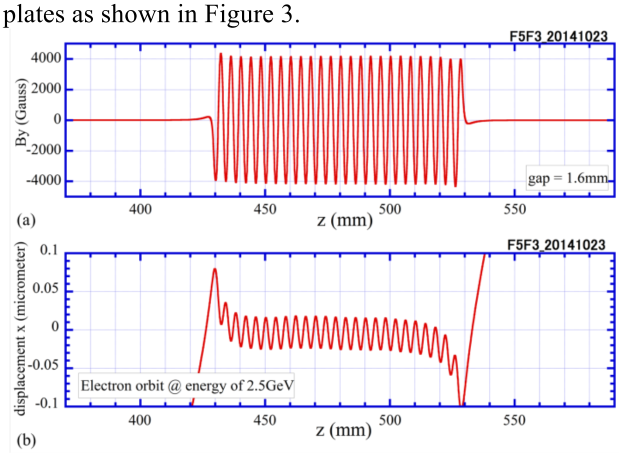

Figure 4: (a) Undulator field of the plate magnet 100mm long with a period length of 4mm measured at a gap of 1.6mm. (b) Orbit of an electron with a 2.5-GeV energy.

The quality of the undulator plate magnet is examined by measuring the magnetic field. The magnetic field in the vertical direction is measured by a Hall sensor, where electric area is 0.05mm × 0.05mm.

The results of the measurements on the undulator field having a 4-mm period length is shown in Figure 4 for 100mm-long plate pair of F3 and F5 (see Figure 2). Figure 4a shows the undulator field and Figure 4b the calculated electron orbit in this field for an electron energy of 2.5GeV. The magnetic field of approximately 4kG was obtained at a gap of 1.6mm. By optimizing the longitudi-

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nal relation between the magnetizing head and the plate magnet, we have a longitudinal field distribution nearly anti-symmetric with respect to the centre of the plate magnet. Symmetric distribution is also possible by optimizing this relation.

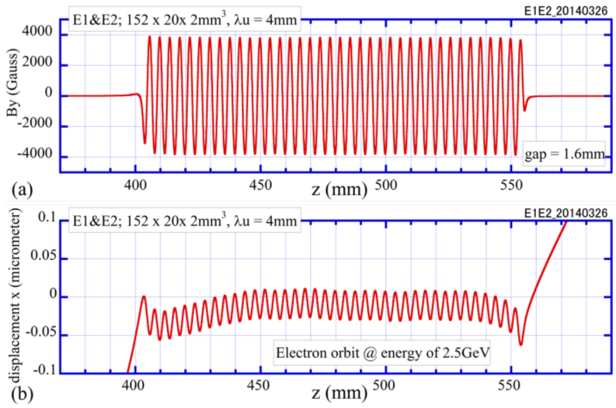

Figure 5: (a) Undulator field of the plate magnet 152mm long with a period length of 4mm measured at a gap of 1.6mm. (b) Orbit of an electron with a 2.5-GeV energy.

Figure 5 shows the result of the measurements in the same manner as in Figure 4, for 152mm-long plate pair of E1 and E2 (see also Figure 2). In both cases, we paid no attention to the magnetization of the end poles at this stage of development. The magnetization for the end poles is made in the same way as for the other inner poles. Although the orbit correction at both ends of the magnetic field is not sufficient in the cases shown in Figures 4 and 5, the orbit in the present undulator field seems satisfactory.

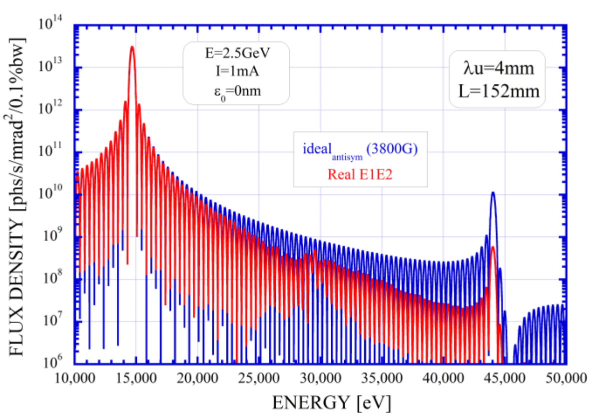

Figure 6: The spectrum calculated on the basis of the measured field compared to that of the ideal field for a 2.5-GeV electron beam with zero emittance and zero energy spread for 152-mm plate magnets (Figure 5).

To examine the present magnetic field, flux-density spectrum was calculated on the basis of the measured data. Figure 6 shows the result for a 2.5-GeV electron energy, zero emittance and zero energy spread, compared to that with the ideal field of the same strength. It is noted that the radiation (red curve) emitted from the present undulator field compares well with that (blue one) emitted from an ideal magnetic field in the region of the fundamental radiation. Nevertheless discrepancy is large in the third harmonic region. For the condition in Figure 6, the fundamental radiation from 10 to 15keV is found to be useful for synchrotron radiation experiments.

Elongation of the Plate Magnet to Build Longer Undulators

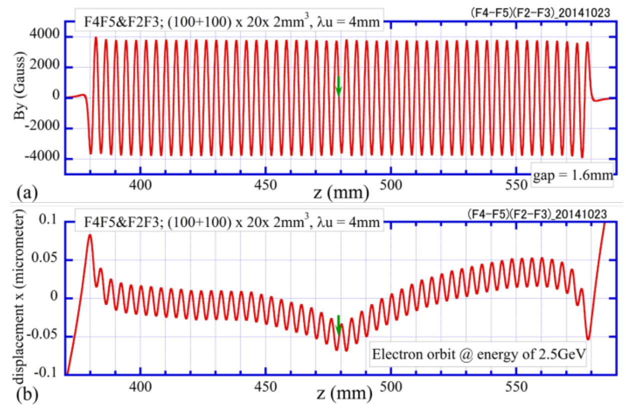

Figure 7: (a) Undulator field 200mm long with a period length of 4mm measured at a gap of 1.6mm. (b) Orbit of an electron with a 2.5-GeV energy. After independent magnetization of the plates, a couple of plates (F2 and F3) is connected to form a field 200mm long, and is opposed to the other couple of plates (F4 and F5).

Fabrication of the 152mm-long magnet plate is a successful example of making longer magnets. However, the length should be limited for fabricating the thin plate magnets. The fabrication of plate magnets longer than 200mm may not be easy when the thickness is 2mm or less. Therefore, a method is required to connect the plates longitudinally. This may be made by adjusting the magnetization strength at the end poles and by optimizing the longitudinal spacing between the plates.

Figure 7 shows the result of trial connection of 100mm-long plate magnets. In this trial a pair of the opposed plates 100mm long, F5 and F3, is just connected longitudinally by the other plate pair, F4 and F2, of the same shape. These plates are magnetized independently by the same method as for F5 and F3 so that they should have anti-symmetric field distribution. The measurement was made at the same gap of 1.6mm. Although a small kick is seen at the connection point denoted by a green arrow (Figure 7b), a spectrum calculation shows that the field (Figure 7a) is suitable for an undulator 200mm long [8].

However, when we try to construct a much longer undulator by connecting many plate magnets, accumulation of the kicks in the orbit at each connection point should not be negligible any more. In order to resolve this issue we developed another new method of magnetization [9, 10]. Here two plate magnets (F9 and F10) 100mm long are connected longitudinally as one plate. Then they are magnetized and placed in opposition to the other plates (F7 and F8) magnetized in the same way. The result of the magnetic measurement made at a gap of 1.2mm is

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shown in Figure 8. The field distribution is anti-symmetric as in the case of Figure 7. It should be noted that the error in the electron orbit at the connection point (denoted by a green arrow) is negligibly small as seen in Figure 8. The result of the spectrum calculation shows that the long undulator field obtained by the present method is quite suitable for synchrotron radiation experiments.

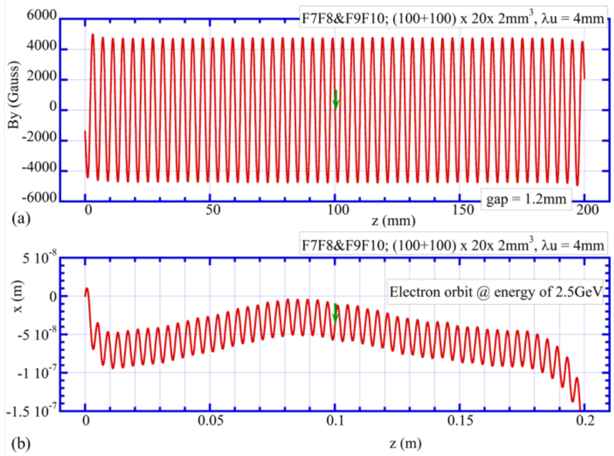

Figure 8: (a) Undulator field 200mm long with a period length of 4mm measured at a gap of 1.2mm. (b) Orbit of an electron with a 2.5-GeV energy. A couple of plates (F7 and F8) is connected longitudinally and magnetized to form a field 200mm long. Then it is opposed to the other couple (F9 and F10) magnetized in the same way.

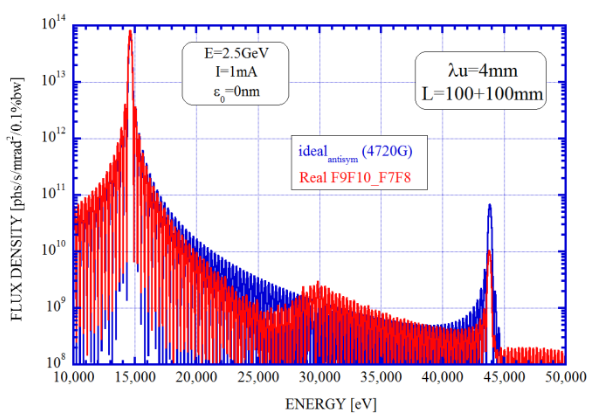

Figure 9: The spectrum calculated on the basis of the measured field compared to that of the ideal field for a 2.5-GeV electron beam with zero emittance and zero energy spread for 200-mm plate magnets (Figure 8).

The present progress in the magnet connection leads to building undulators as long as we desire. Figure 10 shows an example of five-plate connection. Five plate magnets 100mm long each are connected longitudinally and then magnetized successively. A series of five plates (Fs1, Fs2, Fs3, Fs4 and Fs5) is placed in opposition to the other series (Fs6, Fs7, Fs8, Fs9 and Fs10) to produce the undulator field in the gap between them. Figure 10 shows that there is no significant kick in the electron orbit at four connection points, which is very suitable for the undulator.

The result of the calculation of flux density spectrum is shown in Figure 11. It shows that the undulator field obtained by this five-plate connection is quite satisfactory and useful.

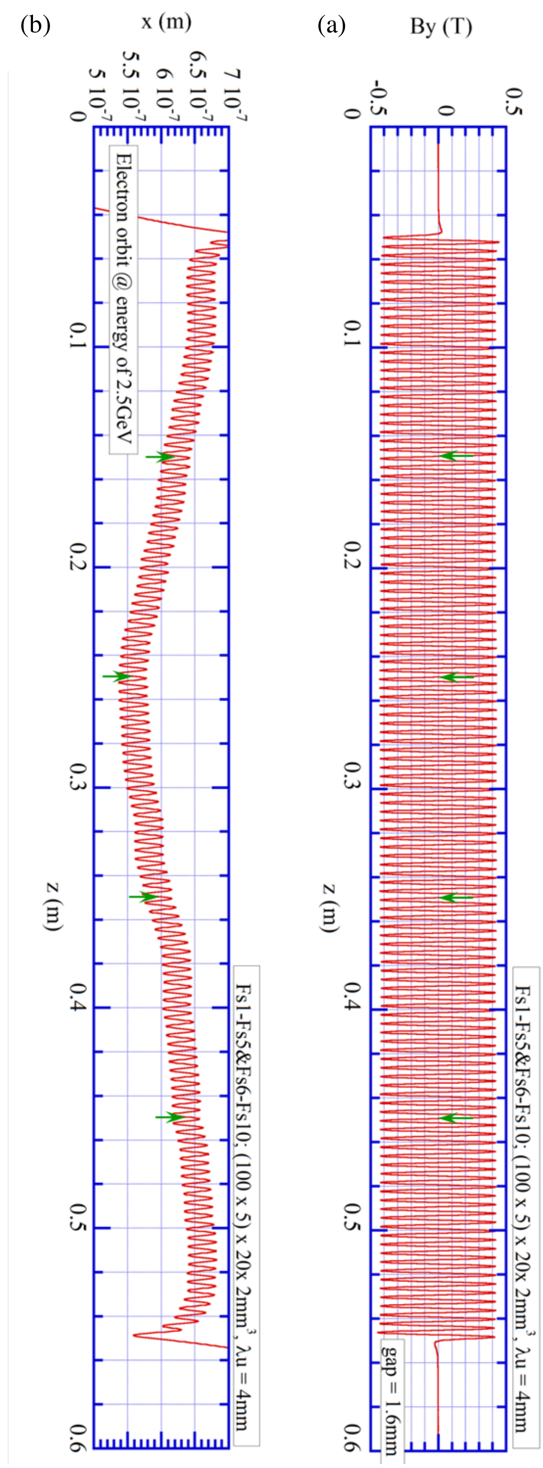

Figure 10: (a) Undulator field 500mm long with a period length of 4mm measured at a gap of 1.6mm. (b) Orbit of an electron with a 2.5-GeV energy. A series of five plates (Fs1, Fs2, Fs3, Fs4 and Fs5) is connected longitudinally and magnetized to form a field 500mm long. It is then

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opposed to the other series (Fs6, Fs7, Fs8, Fs9 and Fs10) magnetized in the same way.

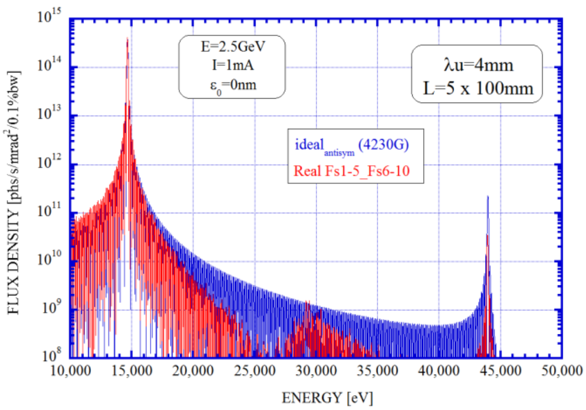

Figure 11: The spectrum calculated on the basis of the measured field compared to that of the ideal field for the 2.5-GeV electron beam with zero emittance and zero energy spread for the 500-mm plate magnets (Figure 8).

CONSTRUCTION OF THE UNDULATOR FRAMES FOR PRACTICAL USE

In order to install the above-mentioned very-short-period undulator magnets, we designed and constructed two types of the undulator mechanical frames as shown in Figure 12. The shorter type (Figure 7a) allows installing the plate magnets with a total length up to 200mm, whereas the longer type (Figure 7b) allows installing the magnets with a length up to 500mm. Both frames have a vacuum chamber and are completed as the in-vacuum undulator. The gap accuracy of both frames is as small as 0.1×10^{-3}mm.

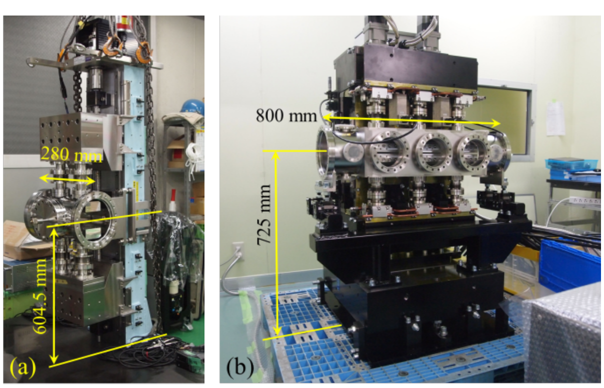

Figure 12: (a) Undulator mechanical frame which allows incorporating magnets with the length up to 200mm. (b) Mechanical frame able to incorporate the magnet length up to 500mm.

They are under preparation for experiments using two different beams: one from a conventional S-band linac and the other from a laser-wake-field acceleration. We believe that experimental evaluation of radiation emitted from these undulators based on the real high-quality electron beams could be achieved in the near future.

CONCLUSION

The effective and stable method to magnetize the plate magnets is well established by adopting the multipole-magnetizing method to fabricate very short-period undulator magnets. When it is applied to the 4-mm period length, a very stable undulator field is produced in the gap between the opposing plate magnets. This method is successfully extended to longer undulator fields by connecting the plural plate magnets.

The mechanical frames as in-vacuum-type undulators are established and completed to install the plate magnets. Evaluation experiments on synchrotron radiation emitted from these very short-period undulators based on the real electron beams will be made in the near future.

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REFERENCES

[1] S. Yamamoto, "A novel attempt to develop very short period undulators", *Journal of Phys.: Conf. Ser.*, vol. 425, p. 032014, 2013.

[2] S. Yamamoto, "Development of the Very Short Period Undulators", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, paper WEOAA02, pp. 1845-1857.

[3] S. Yamamoto, "Undulator Development Towards Very Short Period Lengths", *Synchrotron Radiation News*, vol. 28, no.3, pp. 19-22, 2015.

[4] S. Yamamoto *et al.*, "In - vacuum undulator installed in a 6.5 GeV storage ring for producing brilliant 14.4 keV Mössbauer photons", *J. Appl. Phys.*, vol. 74, p. 500, 1993, https://doi.org/10.1063/1.355260

[5] *e.g.* http://www.spring8.or.jp/
http://www.psi.ch/sls/
http://www.lunduniversity.lu.se/research-and-innovation/max-iv-and-ess

[6] S. Yamamoto *et al.*, "Construction of a Very Short Period Undulator, SGU # 17 and the Photon Factory Upgrade", *AIP Conf. Proc.*, vol. 879, p. 384, 2007, https://doi.org/10.1063/1.2436080

[7] S. Yamamoto *et al.*, "Development of the Short Gap Undulators at the Photon Factory, KEK", *AIP Conf. Proc.*, vol. 1234, p. 599, 2010, https://doi.org/10.1063/1.3463278

[8] S. Yamamoto, "Development of undulator magnets towards very short period lengths", *AIP Conf. Proc.*, vol. 1741, p. 020029, 2015, https://doi.org/10.1063/1.4952808

[9] S. Yamamoto, "Development of very short period undulators III", in *Proc. the 13th Annual Meeting of the Particle Accelerator Society of Japan*, Aug. 2016, Chiba, Japan, 2016, paper TUP066, pp. 1035-1039, in Japanese.

[10] S. Yamamoto, "Development of a Novel Undulator Having Very Short Period Lengths", presented at the 8th Int. Particle Accelerator Conf. (IPAC'17), Copenhagen, Denmark, May 2017, paper TUPA061.