A novel attempt to develop very short period undulators

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Abstract. We are exploring a novel method to fabricate undulator magnets having a very short period. We have succeeded in producing a 100-mm long magnet plate with 4-mm period length, which gives an undulator field of approximately 7kG at a “virtual gap” of 1.2mm. A spectrum calculation shows that the quality of the radiation emitted from this magnetic field is satisfactory for the fundamental radiation as compared to the ideal undulator field.

1. Introduction

The energy of photons from undulators is inversely proportional to the period length of the undulator field and proportional to the square of the electron-beam energy. Hard x-ray radiation was usually generated with in-vacuum undulators with period lengths of several cm installed in electron storage rings with 6-8GeV energies[1, 2]. Construction of newer sources has recently been planned and partly realized in compact 3rd generation light sources with in-vacuum undulators of period lengths around 20mm [3]. This was preceded by the construction of three in-vacuum-type undulators at the Photon Factory (PF), High Energy Accelerator Research Organization, KEK. It proved that these short gap undulators were very useful as hard x-ray sources in the 2.5-GeV storage ring [4, 5].

As the next step, we have been exploring a method to fabricate very short period undulators. Here, “very short period” means periods one order-of-magnitude shorter than the ordinary period of several cm. We are developing a plate-type magnet some 100mm long with a period length of 4mm in the longitudinal direction. We selected 4-mm period since we can generate 12-keV radiation with the first harmonic of this undulator in the 2.5-GeV storage ring. The very short period undulators operate in a gap one order-of-magnitude shorter than that of ordinary undulators. Thus these undulators are very useful when they are combined with very low emittance storage rings and linacs.

A multi-pole magnetizing method was applied to magnetizing this plate: a periodic undulator field (of 4-mm period in this case) was generated by pulsed electro-magnets, and was transcribed into the plate. The magnetization procedure allows the undulator field to be obtained in a very short gap between the pair of opposing plates. In this paper we report the magnetization method to obtain a very short period and present the test results.
2. Formation of a very short-period undulator field

A multi-pole magnetizing method of a thin plate is shown schematically in figures 1 and 2. The plate is made of Nd-Fe-B type magnetic material. It is embedded between a pair of flat electromagnets having a zigzag wire. By applying a pulsed current to these electromagnets, N- and S-poles are formed simultaneously in the plate with a periodic spacing. After the magnetization, a pair of these plates is combined with faces opposing each other, and the magnetic field is produced in the short gap between the plates. In figure 1a, the magnetization direction is perpendicular to the plate surface (the perpendicular case). The geometry is similar to a perpendicular magnetic recording method in a recording media. The other geometry (the longitudinal case) is also possible as shown in figure 2. 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, even if there are errors in the strength of magnetization.

A preliminary magnetization test started with the perpendicular geometry. The test was performed on the magnet plate 100mm long, 20mm wide and 2mm thick, with a period length of 4mm. The plate was made of NEOMAX-48BH with a remanent field of $B_r=13.9$ kG and a coercivity of $iH_c=14$ kOe.
(Hitachi Metals Co. Ltd.). However, the result was not satisfactory at all for the undulator field.

Deviations in both magnetic field strength and period length were as large as $\pm 50\%$ and $\pm 30\%$, respectively. We found this result to be due to the improper fabrication of the electromagnets in the magnetizing head. In order to simplify the procedure to fabricate the magnetizing head and to obtain a successful result with reduced number of processes, we adopted a different method while keeping the perpendicular geometry. This method allowed the same plate to be magnetized by the moving head which was driven stepwise by a linear motor as shown in figure 3.

We devised a one-period (or two-pole) magnetizing head in which the wire with a diameter of 1.1mm was fixed tightly with an epoxy resin. An accuracy of the periodic spacing between the magnetic poles is 0.05mm. The wire was wound twice around each pole. The head was excited by applying a pulsed current of 9.6kA during 0.1msec to the magnetizing head. The step width of the moving head was set to the period length of 4mm of the magnetic field. The head movement on the linear motor was controlled by a closed loop scheme with an accuracy of 0.003mm. The accuracy of the period length of the plate magnetic field was mainly determined by the accuracy of the spacing of the wires in the head and of the step widths of the head driven by the linear motor. Thus, the accuracy of the achieved field strength was essentially affected by the accuracy of the period length and of the quantity of the electric charge applied to the head at each step.

![Figure 3. Perpendicular magnetization employing a linear motor.](image)

### 3. Magnetic field measurements and characterization

The quality of the magnet plate for an undulator was examined by measuring the magnetic field. The magnetic field in the vertical direction was measured by a scheme shown in figure 4. Here the electric area of the Hall probe (Nihon Denji Sokki Co. Ltd.: A8083-A6211) was placed in the bottom part of the probe holder. Twice the value of the measured field strength was employed as a measure of the magnetic field of the “virtual undulator”. This value means a “virtual undulator field”, which is given by a superposition of the measured field and the mirror image field at a “virtual gap” of $g = 2(g_1 + g_2)$. Here $g_1$ is the gap between the top surface of the plate and the bottom surface of the Hall probe holder and $g_2$ is the separation between the holder bottom and the centre of the hall probe. The spatial resolution of the Hall probe was 0.05mm, and $g$ was 1.2mm ($g_1 = 0.2mm$, and $g_2 = 0.4mm$), whereas the total thickness of the Hall probe holder was 3mm.

![Figure 4. Magnetic measurement of the magnet plate, where a “virtual gap” is given by $g = 2(g_1 + g_2)$.](image)

The measurement of the “virtual undulator field” is shown in figure 5. Figure 5a shows the undulator field and figure 5b shows the electron orbit in this field for an electron energy of 2.5GeV. The magnetic field of approximately 7kG was obtained at a “virtual gap” of 1.2mm. Magnetization of the end poles was accomplished in the same way as for the other inner poles at this stage of the development. Although the orbit correction at both ends of the magnetic field was not sufficient with the present magnetization method, the orbit in this “virtual undulator” may be satisfactory. To examine the present field, the spectrum of the flux density was calculated on the basis of the measured data. Figure 6 shows the result in a case of 2.5-GeV electron energy, zero emittance and zero energy spread, compared to that with the ideal field of the same strength.
It should be noted that the radiation from the “virtual undulator field” compared well with that from an ideal magnetic field in the region of the fundamental radiation, though discrepancy was large in the third harmonic region. For the condition in figure 6, the radiation from 10 to 15keV was found to be useful for synchrotron radiation experiments.

![Figure 5](image)

**Figure 5.** Measurement of the “virtual undulator field” with a period length of 4mm; (a) the undulator field and (b) the electron orbit displacement when the electron energy was 2.5GeV.

4. Conclusion
The present results indicate that we are in the right direction for the development of very short period undulators. The construction of undulators for practical use would require overcoming a number of issues such as improvements in the magnetization intensity and accuracy, the development of magnetization methods for the two ends of the undulator, and the development of precise magnetic field measurement methods in the very short gap, etc. Further we have to investigate light-source accelerators that can accommodate this type of undulators with very short gaps. We believe, however, that the very short period undulators provide increased flexibility to pursue the “ultimate” light sources, since the straight section length that these undulators require is obviously very short.

![Figure 6](image)

**Figure 6.** (a) Flux density spectrum calculated on the basis of the measured field, compared to that of the ideal field in case of 2.5-GeV energy of the electron beam with zero emittance and zero energy spread. (b) The energy region of the fundamental radiation expanded.

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