PROOF-OF-PRINCIPLE EXPERIMENT OF PHASE-COMBINED UNDULATOR

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Abstract

A simple arrangement of undulator magnets having nearly zero magnetic force between the upper and lower magnet arrays, which has been proposed as a phase-combined undulator (PCU), is experimentally demonstrated. In PCU, each magnet array is divided into a number of sections, half of which are phase-shifted according to a particular rule without breaking the periodic condition required for the undulator field. Magnetic field and force in PCU with two conditions are measured and compared with the conventional Halbach array. The experimental results show that the magnetic attractive force in the undulator is drastically reduced, showing the feasibility of the PCU concept.

INTRODUCTION

Variable-gap undulators usually require rigid mechanical components and frames to control the magnet gap precisely against the large attractive force. This in turn gives us a new concept of undulator design; if the attractive force is cancelled out, the heavy and large mechanical frame is no longer required, and then the undulator can be much more lightweight and compact. A new undulator concept based on a cost-effective force cancellation system has been proposed at SPring-8 [1], which takes advantage of multipole monolithic magnets [2, 3]. The lightweight, compact, and cost-effective undulator based on the force cancellation system is also presented in these proceedings [4].

In a former paper [5], we proposed another solution for the lightweight, compact and cost-effective undulator referred to as a phase combined undulator (PCU), which is based on a special magnetic circuit having intrinsically no net magnetic force without any force cancellation system. In this paper, we show the result of the proof-of-principle experiment of PCU.

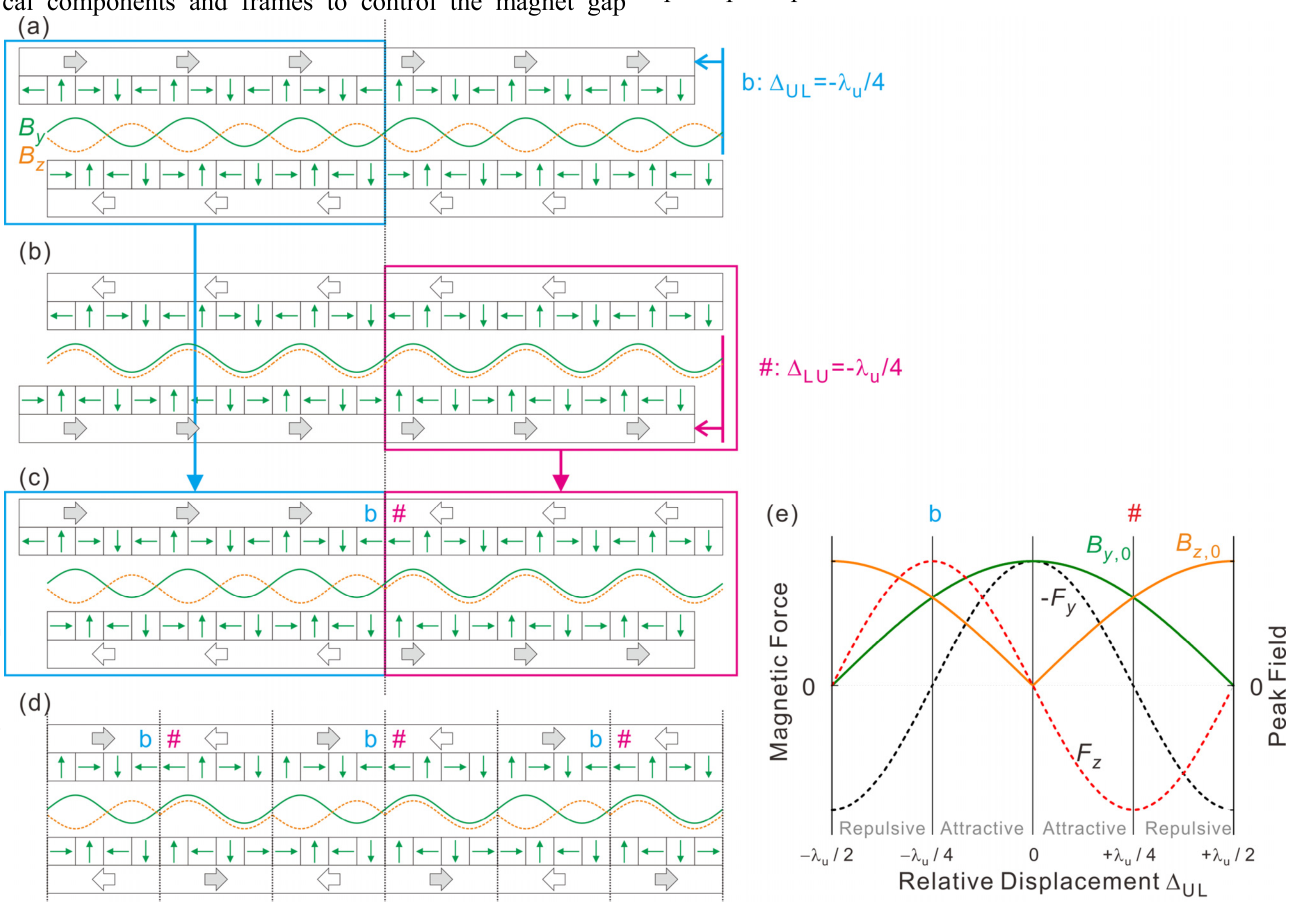

Figure 1: Conceptual drawing of (c) PCU2 ($D = 2$) and (d) PCU1 ($D = N_u$) as a combination of (a) positive and (b) negative shear [1]. Symbol b indicates that the upper magnets is displaced by $\Delta_{UL} = -\lambda_u/4$ in the section, and symbol # indicates that the lower magnets is displaced by $\Delta_{LU} = -\lambda_u/4$ as shown in (e) the phase diagram.

EXPRIMENT

Figure 1 shows the conceptual drawing of (c) PCU2 ($D = 2$) and (d) PCU1 ($D = N_u$) as a combination of (a) the positive- and (b) negative-shear magnetic array, where D denotes the number of sections to be explained later in more detail and N_u is the number of periods. Symbol b indicates that the upper magnets is displaced by $\Delta_{\mathrm{UL}} = -\lambda_{\mathrm{u}}/4$ in the section, and symbol # indicates that the lower magnets is displaced by $\Delta_{\mathrm{LU}} = -\lambda_{\mathrm{u}}/4$. In PCU, (a) the positive and (b) negative shear forces, which appear at the non-zero phase shift, are combined to cancel out $F_z$with keeping the periodicity of B_y. The polarity of B_z flips every other sections, which results in the periodicity with a longer period than λ_{u}. The periodicity change in B_z obviously has little impacts on the radiation properties but may have some on the electron beam dynamics, which is to be discussed elsewhere.

The number of sections D ranges from 2 to N_u, and smaller D results in a smaller residual attractive force, but larger tensile and compression force inside the magnetic girder.

In this paper, we show experimental results carried out with two different conditions with $D = N_u$ (PCU1), and $D = 2$ (PCU2), and compared them with that of a normal Halbach array, whose magnet configurations are schematically shown in Fig. 2. The period is 32 mm, the periodic number is 44, and the total length is 1.5 m. The magnets has the remanent field B_r of 1.2 T and the dimensions of $45 \times 11.5 \times 8$ mm. The end magnets are configured so that first and second field integral are ideally zero in the all configurations.

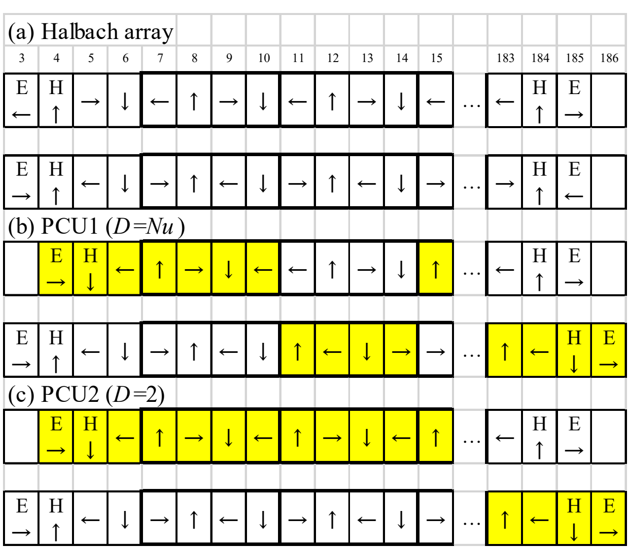

Figure 2: Magnet arrangements in the (a) Halbach array, (b) PCU1, and (c) PCU2. Here white box and the arrow inside indicate the magnet and its magnetization direction. The yellow magnets in PCU indicate magnets has been moved from the original Halbach array. Symbol H and E indicate the special end magnets having the thickness of 4 and 4.8 mm, respectively.

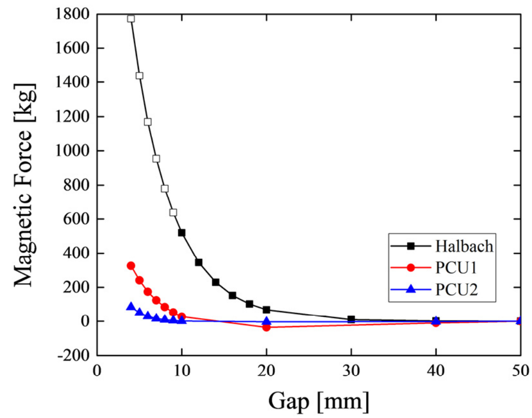

Figure 3: Magnetic force measured by the strain-gauge load cell in Halbach (black square measured, white square extrapolated), PCU1 (red circle) and PCU2 (blue triangle).

Figure 3 shows the measured results of the magnetic force in the three magnet configurations, where the PCU arrays demonstrated much lower magnetic force than the Halbach array. At the gap of 8 mm ($g/\lambda_{\mathrm{u}} = 1/4$), the attractive force in the PCU1 and PCU2 were successfully reduced to 11 % and 1 % of that in the Halbach array. Note that the small residual force at the extremely small gap, which comes from the finite magnetic susceptibility of the permanent magnets and the effect of the section junctions, can be further suppressed with additional adjustment methods described in Ref. 5.

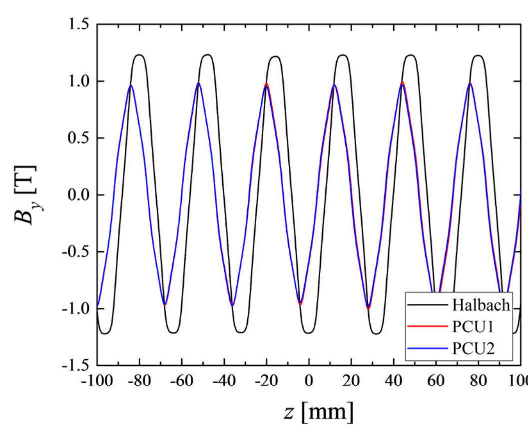

Figure 4: Measured magnetic field in the Halbach (black), PCU1 (red) and PCU2 (blue) at the gap of 4 mm. Results only near the undulator center are shown.

The measured results of the field profiles are shown in Fig. 4. The peak field amplitudes were 0.97 T for both the PCU1 and PCU2, while that of the Halbach array was 1.2 T. This difference has been predicted by the analysis made in Ref. 5 and thus the PCU is much suitable for the long period undulator in which the requirement of the field strength is relaxed.

ISBN 978-3-95450-182-3

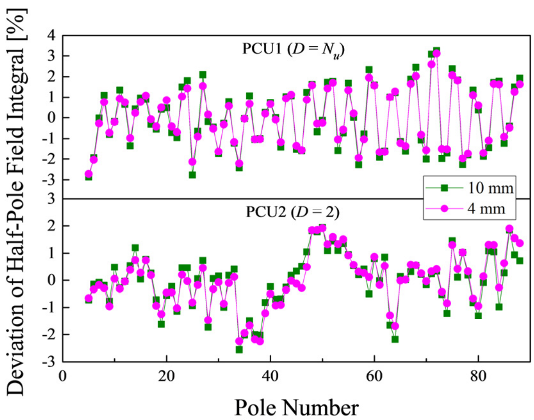

Figure 5: Deviation of half-pole field integral in PCU1 (upper) and PCU2 (lower).

The undulator performance is related to the field uniformity along the undulator axis, which is shown in Fig. 5 in terms of the half-pole field integral as a function of the pole number for two different gap values of 10 mm and 4 mm. Although the variation according to the gap change is negligibly small, we should mention an apparent systematic error specific to the PCU configuration besides the intrinsic error coming from the permanent magnet blocks. Namely, the half-pole field integral oscillates with the period of $2N_u\lambda_\mathrm{u}/D$; the oscillating period is $2\lambda_\mathrm{u}$ for $D = N_u$, while it is $N_u\lambda_\mathrm{u}$ for $D = 2$. Note that the latter is not so obvious, however, we find that the average of the half-pole integral in the 1st half is about 1 % higher than that in the 2nd half, corresponding to the oscillating period of $\mathrm{N_u}\lambda_\mathrm{u}$. We should stress here that these oscillating behaviours come from a systematic measurement error, i.e., the misalignment (tilt) of the Hall probe to measure the magnetic field. The vertical field measured by the tilted probe is given by $B_{y,\mathrm{m}} = B_{y,\mathrm{r}} + \alpha B_{z,\mathrm{r}}$, where the subscripts *m* and *r* mean measured and real value, respectively. Recalling that $B_{z,\mathrm{r}}$ has the periodicity as shown in Fig. 1 (c) and (d), it is easy to understand that $B_{y,\mathrm{m}}$ has the periodicity discussed above.

We actually found that an assumption of the tilt angle of around 0.6 degrees reproduces the both results of the PCU1 and PCU2.

The effects of B_z discussed above degrade the apparent field quality in the PCUs and increase the apparent phase error. To properly measure and evaluate the field quality of the undulator having the B_z component, we need to evaluate the tilt angle of the Hall probe and measure the B_z component to compensate the B_y data.

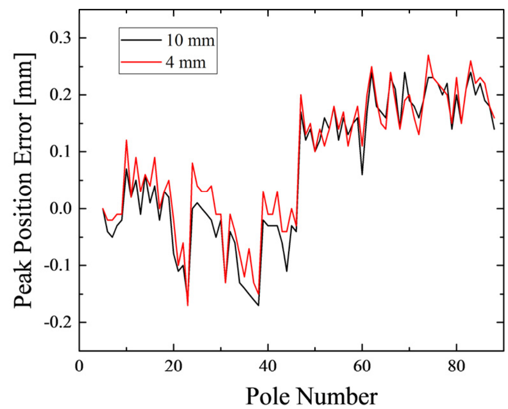

Figure 6: Peak position error in the PCU2.

Figure 6 shows the position error of B_y peaks in the PCU2. There are about 0.2-mm jump at the center and the jump is constant regardless of the gap. This may mean that there exists a 0.2-mm spacing between the two adjacent magnets around the center because the magnetic girder made by aluminium was yielded by the large tensile force of the PCU2 as shown in Fig. 1 (c). It should be noted, however, that the tensile force in the PCU2, which is half of the attractive force in the Halbach array and is 2.7/2 t at the gap of 2 mm, is about 1/100 of the tensile strength of the magnet girder having the proof stress of 275 MPa and the cross section of 4520 mm^2.

The real reason of the peak position error is the apparent rotation of the magnetic axis of the permanent magnet due to its finite susceptibility. The magnetic axes are slightly rotated by θ counterclockwise and clockwise in the upstream and downstream, respectively, where θ is estimated as 1.1 degree with the relation $\theta \approx \pi\, 0.2\ \mathrm{mm}/32\ \mathrm{mm}$. Although this causes the phase jump at the center, its impact on RMS phase error over the total length is negligible when the periodic number is not enormously small. Moreover, it can be vanished by previous noted additional adjustment methods.

ACKNOWLEDGEMENT

We would like to thank T. Kohda at NEOMAX ENGINEERING Co., Ltd for discussing re-arrangement of the magnets.

REFERENCES

[1] R. Kinjo, T. Seike, A. Kagamihata, S. Yamamoto, and T. Tanaka, in Proc. 36th Int. Free Electron Laser Conf. (Basel, Swiss, 2014), MOP023.

[2] S. Yamamoto, J. Phys.: Conf. Series 425, 032014 (2013).

[3] S. Yamamoto, in Proc. 5th Int. Particle Accel. Conf. (Dresden, Germany, 2014), WEOAA02.

[4] R. Kinjo et al., presented at IPAC'17, Copenhagen, Denmark, May 2017, in this proceedings, paper TUPAB052.

[5] R. Kinjo and T. Tanaka, Phys. Rev. ST Accel. Beams. 17, 122401 (2014).