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Selected novel hybrid/permanent magnet (hybrid/PM) configurations as elements of high-field helical undulators are considered. The general approach is found to be capable of attaining on-axis magnetic field amplitudes exceeding 0.4 T for a 0.5:1.0 gap:period ratio and at least two of the configurations can be constructed exclusively out of steel and permanent magnet monoblocks. Such simplified magnetic structures can improve the effectiveness and economy of small-scale, short-period undulator designs.

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AN ECONOMICAL HIGH-FIELD HYBRID/PM HELICAL UNDULATOR SCHEME

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Abstract

Selected novel hybrid/permanent magnet (hybrid/PM) configurations as elements of high-field helical undulators are considered. The general approach is found to be capable of attaining on-axis magnetic field amplitudes exceeding 0.4 T for a 0.5:1.0 gap:period ratio and at least two of the configurations can be constructed exclusively out of steel and permanent magnet monoblocks. Such simplified magnetic structures can improve the effectiveness and economy of small-scale, short-period undulator designs.

1. Introduction

Among the problems associated with the segmentation of small-scale undulator periods perhaps the most significant relate to tolerances on allowable machining, magnetization, and alignment errors, which become rapidly more difficult to satisfy as the number of segments per period is increased while the period is reduced. For example, planar undulator designs based on the Halbach configuration include eight separate pieces of permeable and (or) permanent magnet (PM) material, making the configuration a difficult candidate for extreme period reduction [1]. The difficulties are compounded if we try to use a pair of the planar structures to create a helical design. In earlier work, some attempts to resolve or mitigate these and other problems have been reported. In certain hybrid/PM and pure-PM schemes [2,3,4] the periodic profiles of the magnetic field were generated primarily by surface profiles machined into two or four monoblocks. None of these designs utilized individual PM segments or steel blocks within a single period. However, schemes [2,3] provide only about one half of the maximum mid-plane field attainable with the Halbach configuration. Scheme [4] gives a small increase of the magnetic field in comparison with the configurations of [2,3]. In an attempt to mitigate the segmentation problem further without sacrificing field strength some novel schemes utilizing steel monoblocks and bias PMs were recently investigated by us [5,6]. Scheme [6] in particular provides a comparatively high magnetic field amplitude. Following these initial efforts, we have continued to develop the concept of an undulator structure based on monoblocks. In the present paper we report on selected hybrid/PM helical undulator configurations which can provide high on-axis magnetic field amplitudes.

2. The general design

A schematic view of one of the undulator designs which utilizes monoblocks together with a minimal number of PM segments per period is shown in Fig. 1. The full assembly consists of four identical arrays and creates a circular magnetic gap (Fig. 1a). Each pair of opposed arrays - which correspond to the X-axis and Z-axis - provide, respectively, the horizontal and vertical components of the undulator's field. A single array consists of a steel monoblock (1) with a periodic structure (λ_w) machined into the poles; two PM monoblocks (2); a single large PM monoblock (3); and a set of two individual PM bias pieces (4) per period. An example of the magnetization directions of the magnetic flux sources is marked by the arrows. All the magnetization vectors of the PMs lie in the X-Z

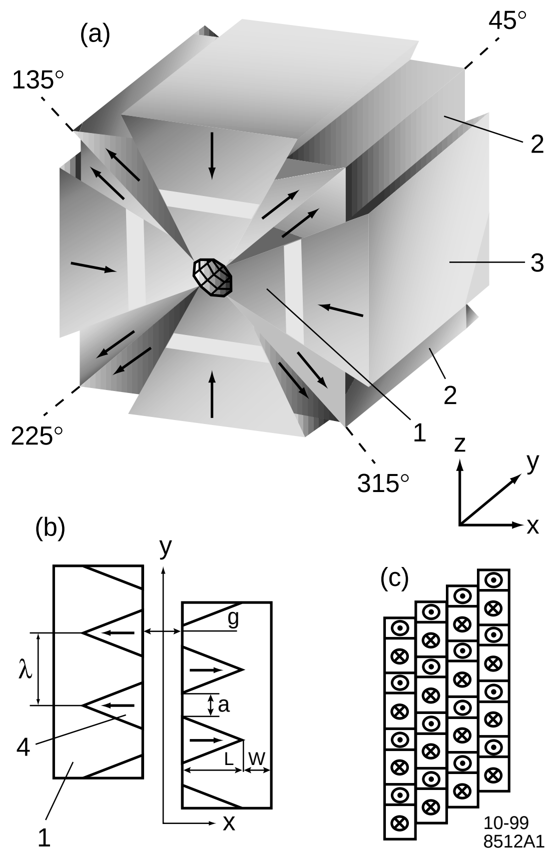

Figure.1. Schematic view of an undulator design. a) - general view; b) - internal magnetic structure of the opposed arrays; c) - pole tip positions in a helical mode. 1 - steel monoblock; 2,3 - PM monoblocks; 4 - bias PMs.

plane. The steel monoblocks in each of the two opposed arrays are shifted relative to each other along the Y-axis by the value $\lambda_w/2$, (Fig. 1b). The longitudinal positions of the PM monoblocks are fixed with respect to the steel monoblocks which they surround. The vertical set of two opposed arrays can be shifted along the undulator axis relative to the horizontal set. This shift (denoted by P - see Fig. 1c) changes the phases of the vertical vs. horizontal on-axis field components, B_x (= $B_0 \cos(2\pi y/\lambda_w)$) and B_z (= $B_0 \cos(2\pi(y+P)/\lambda_w)$). This provides a smooth change of polarization of the radiation from linear (P = 0) to circular ($P = \lambda_w/4$).

An alternative helical design based on longitudinally sheared magnetic structures is shown in Fig. 2. The pole surfaces of all the blocks in each array are inclined with respect to the X-Z plane so as to generate a definite chirality in the magnetic field with respect to translation along the Y-axis. In the depicted array all the blocks have equal inclination.

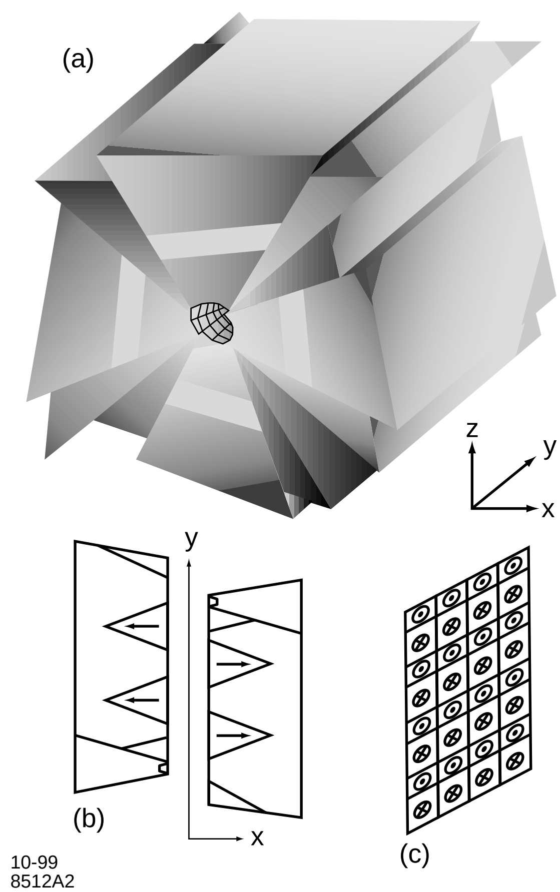

Figure 2. Schematic view of an undulator design with inclined magnetic structure. a) - general view; b) - internal magnetic structure of the opposite arrays; c) - pole tips positions in a helical mode. 1 - steel monoblock; 2,3 - PM monoblocks; 4 - bias PMs.

The helical design is created by means of placing the four arrays at angles of 0, $\pi/2$, π and $3\pi/2$ around the Y-axis and then shifting them (with reference to the first array) by the values of P, $\lambda_w/2$ and $\lambda_w/2 + P$ along the undulator axis. If the shift P is equal to $\lambda_w/4$ we can choose the inclination δ_y (the displacement of the top (+) vs. bottom (-) points of the pole tip along the undulator axis) so that the pole tips form a spiral around the magnetic gap (see Fig. 2c). In this design $\delta_y = \lambda_w/8$. One can see that the longitudinal segmentation of the described magnetic structures (four separate pieces per period) is less complicated than that of most alternative high field hybrid designs. For example, design [7] includes thirty-two separate pieces per period. This constitutes an important difference for the fabrication of small-scale magnetic structures. As a next step in this direction we considered designs wherein the magnetization directions of the PMs (2) and bias PMs (4) are the same. In such cases we can combine the separate bias PM pieces with the monoblocks (2). One quarter of the magnetic structure of this novel construction is shown in Fig. 3.

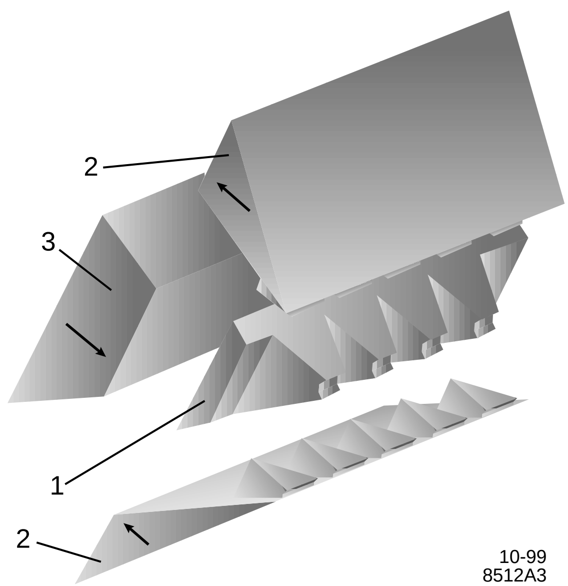

Figure 3. Array components for a pure monoblocks undulator design. 1 - steel monoblock; 2 - PM monoblock with integrated bias magnet array; 3 - PM monoblock.

3. Undulator field properties

In all the configurations considered by us three groups of PMs are used to generate the on-axis magnetic field of the opposed arrays. One group of PMs (4) provides a circulation of magnetic flux about the undulator axis. Two PMs (3) give an undulator field component formed by the superposition of the oppositely-directed and modulated magnetic fluxes of both steel blocks (1). It is evident that the magnetization directions of

PMs (4) and (3) have to be opposite to each other. PMs (2) amplify the modulation of the magnetic flux near the undulator axis and their magnetization directions can be optimized. We investigated different magnetic field distributions in a number of our designs using the 3D-code RADIA [8] and optimized the parameters for a 1:2 gap:period ratio (with λ_w=1cm). Four sets of magnetization directions of PM groups (2) and (4) (with group (3) magnetized accordingly) were considered (see Fig. 4). The long arrows coinciding with the X and Z axes correspond to the magnetization vectors of PM group (4). The arrows of PM group (3) are not shown. Cases A(m) and B(m) correspond to designs based exclusively on monoblocks.

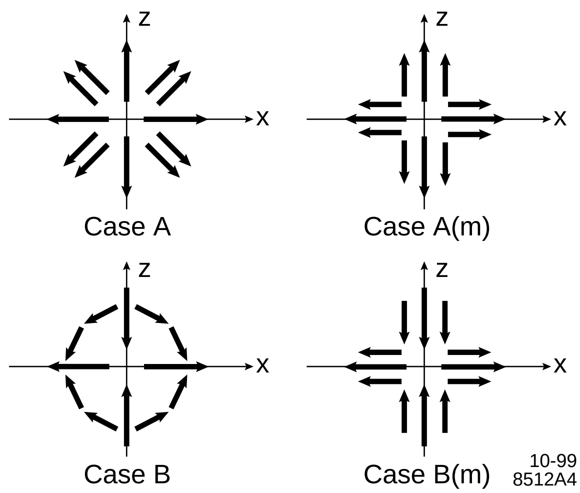

Figure 4. Four sets of magnetization directions of PMs (2) and (4) used in the calculations. The two vectors adjacent to each on-axis vector denote the magnetization directions of PMs (2). Case A - four identically magnetized arrays; Case A(m) - monoblock design (i. e., PMs (2) and (4) in each array machined out of a single block) ; Case B - inverted magnetization direction of PM set (4) in the vertical array pair (vis-a-v-s Case A) and a 90° (or -90°, as appropriate) rotation in the magnetization directions of PMs (2) ; Case B(m) - same as Case A(m) but with inverted magnetization directions in the vertical pair of PM monoblocks

The contributions to the total undulator field from PM groups (4), (3) and (2) can vary depending on the particular distribution of magnetizations and the design. In our calculations these groups were found to generate, respectively, 42 - 84, 37 - 0.8 and 60 - 14 per cent of the total field for g=λ_w/2, a=λ_w/3, L=λ_w, W=λ_w/2, and with the angular size of the permeable blocks (1) set equal to π/4. We used Vanadium-Permendur for the blocks and NdFeB (B_r = 1.2 T) for the permanent magnets in the simulations. The dependencies of the magnetic field amplitudes on the shift P are shown in Fig. 5. Curves 1 and 2 correspond to Case A. Without inclined poles and PM blocks the magnetic field amplitude does not depend on the shift P and B_0 = 0.24 T. With the inclination (Fig. 2) the symmetry between +P and -P is broken. The magnetic field amplitude attains its maximum (B_0 = 0.28 T) when the tip poles form a helical spiral. The monoblock design (Case A(m)) leads to a magnetic field increase (see markers 5 and 6). In Case B the magnetization directions of PMs (4) and (3) are inverted in the vertical assembly. The field maximum is attained when the magnetization vectors of PMs (2) are directed perpendicularly to the side surfaces of the steel blocks. Curves 3 and 4 are similar to curves 1 and 2. Without the inclination of the array structure the helical field is equal to -0.36 T. In the inclined design the magnetic field amplitude attains -0.42 T. In this case the magnetic field decreases when we use the monoblock design (see markers and ■).

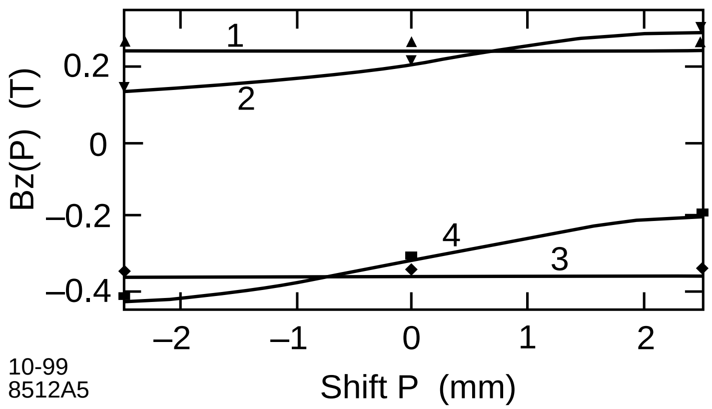

Figure 5. Magnetic field amplitudes and influence of shift P. Curve 1 - Case A, $\delta_y = 0$; Curve 2 - Case A, $\delta_y = \lambda_w/10$; 5- Case A(m), $\delta_y = 0$; 6 - Case A(m), $\delta_y = \lambda_w/10$; Curve 3- Case B, $\delta_y = 0$; Curve 4 - Case B, $\delta_y = \lambda_w/10$; - Case B(m), $\delta_y = 0$; ■- Case B(m), $\delta_y = \lambda_w/10$.

The above-described scheme can provide linearly polarized radiation if we do not use shift P. For Case B(m) and P = 0 we can attain B_0 = -0.44 T.

Fig. 6 illustrates the transverse profiles of the horizontal component of the magnetic field for Case B in the position when $B_x = B_0$ and $B_z = 0$. Both profiles have focusing properties. It is evident that the sign of the focusing will change if we change the inclination of the magnetic structure.

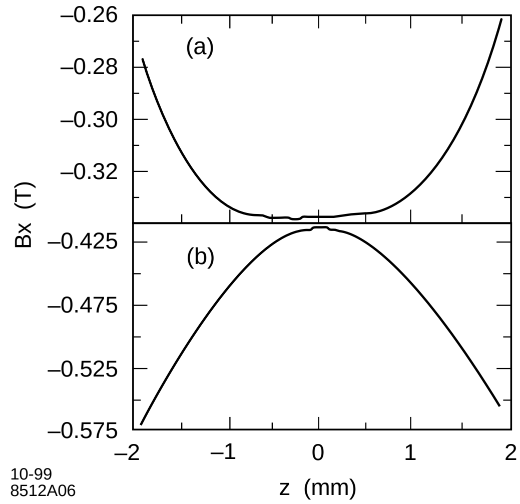

Figure 6. Transverse magnetic field profiles for P = $-\lambda_w/4$. a) - Case B, $\delta_y = 0$; b) - Case B, $\delta_y = \lambda_w/10$.

4. Conclusions

This scheme reported here can attain substantially high magnetic field amplitudes in both helical and planar undulator modes. In addition, the design allows for the exclusive use of steel and PM monoblocks to define the periodic magnetic field. This capability can contribute to future improvements in small-scale undulator technology. One can also easily transform the proposed helical design into planar or elliptical schemes with fully open horizontal (or vertical) gap access. For example, either pair of opposed arrays will constitute a planar design if $\delta_y = 0$ and an elliptical design if the pole tips are round and $\delta_y \neq 0$.

Acknowledgments

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