A SHORT-PERIOD STRONG FOCUSING UNDULATOR SCHEME

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Abstract

A novel short-period hybrid/permanent magnet undulator scheme is considered. The magnetic structure contains no small-scale permanent magnet (PM) pieces or permeable blocks. The small-scale periodic profile of the magnetic field is generated by surface profiles machined into the steel yokes. The structure can attain a magnetic field amplitude of 3.1 kGauss for a gap/period ratio of 1/2 and a (period-averaged) focusing gradient of ~ 500 T/m across a 4.5 mm vertical gap. The gradient value and dipole field are tuneable. Selected results of 3D-simulations of the magnetic field properties and tests of a 9mm-period mock-up structure are discussed.

1 INTRODUCTION

There are a number of well-known problems associated with undulator designs featuring sub-centimetre periods. These include:

a) in segmented magnetic structures, the necessary miniaturisation of the individual pieces (this not only exacerbates the difficulty of manufacturing and assembly, but in the limit can significantly reduce the on-axis field of the structure in contrast to one with a conventional (>1 cm) period);

b) leakage fields (shortening of the undulator period can introduce a rapid increase in parasitic and saturation-related flux leakage, with a corresponding decrease of the mid-plane field);

c) reduced aperture (the ratio of the gap accessible for an electron beam to the magnetic gap rapidly decreases);

d) increased radiation and temperature (irreversible demagnetisation and damage of the permanent magnets are exacerbated due to their increased proximity to the electron beam and its radiation).

In earlier work, some attempts to mitigate these and other problems associated with sub-centimetre period undulators have been reported. In certain hybrid/permanent magnet and pure-PM «micro-undulator» schemes [1,2,3] the periodic profiles of the magnetic field are generated primarily by surface profiles machined into two monoblocks. None of these devices utilise small individual PM pieces or steel blocks. Due to the uncomplicated manufacturing methods, the periods of these structures can be made extremely small, and are limited mainly by material inhomogeneity at microscopic scales [4]. However, schemes [1,2] are limited to only about 0.5 of the maximum mid-plane field B_o typical of the Halbach configuration, which is itself limited to substantially larger sub-centimetre periods [5]. Scheme [3] generates a non-zero average magnetic field for each pair of monoblocks, and must be comprised of sequential monoblock pairs to achieve a small enough value of 1st field integral.

An undulator scheme based on the redistribution of an external longitudinal magnetic field [6], a helical microwiggler scheme [7], and a twisted structure [8] all provide some means for the leakage field compensation and can provide magnetic field values close to B_o. Further extension of schemes [6,7] to millimeter or shorter periods appears to be a problem.

To maximise the gap/period ratio (viz., mid-plane field) for an electron beam of a given diameter, the periodic magnetic structure must be installed in a vacuum chamber (see, e.g., [9]). In this case, the magnetic structure must have a minimal surface area and a special coating to suppress outgasing.

In the present paper we report on a hybrid/PM undulator scheme which promises to mitigate or resolve a number of the problems mentioned in a), b), c), and d). The undulator magnetic field is generated by four steel monoblocks with machined periodic profiles, the geometry provides for a straightforward mechanism of leakage field suppression, and the PM material is substantially removed from the median plane. Noteworthy, the structure also features a significant flexibility for implementing an intense distributed focusing field.

2 THE UNDULATOR SCHEME

A schematic view of the basis undulator design is shown in Fig. 1. The uniform part of the magnetic structure consists of four steel blocks which form right and left yokes (1) with a magnetic gap (g) and two PM blocks (2). Each steel block has a periodic structure (with period λ_w) machined into the poles. The poles have a wedge shape with dimensions h, a, and b in the XZ-plane and an acute angle α in the XY-plane. The right and left parts of the assembly are shifted relative to each other along Z-axis by value $\lambda_w/2$ and along the X-axis by value Δx.

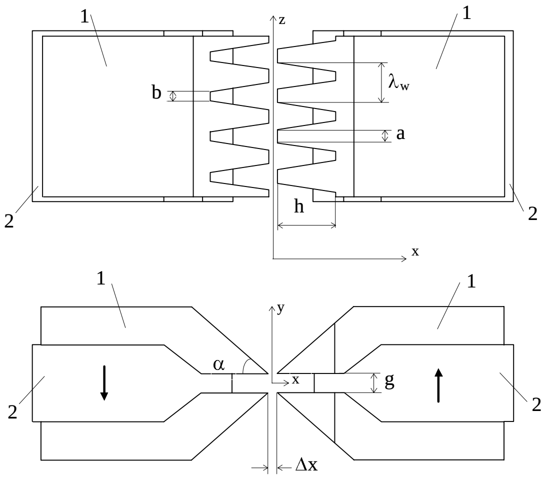

Figure 1. Schematic drawing of the undulator structure: 1 - steel yokes; 2 - permanent magnets.

The undulator magnetic field is created by the superposition of the modulated magnetic fluxes of both yokes. The average value of the on-axis magnetic field is equal to zero. Both the displacement Δx and the specific steel yoke profile provide some amount of leakage flux suppression between poles of the right and left yokes in this scheme (compare to C-shape device in Ref. [10]). Both factors also contribute to the strong field gradient near the undulator axis.

3 MAGNETIC FIELDS

The undulator magnetic field B_y and gradient $G=\partial B_y/\partial x$ depend strongly on the distance Δx between the right and left steel yokes and on the pole shape. Evidently, when the yokes practically touch each other ($\Delta x<0$) both B_y and G tend to zero. When the distance Δx is positive and large ($\Delta x >> g$), then B_y and G $\rightarrow$ 0 again. An analysis of the magnetic field distributions shows, that the maximal values of B_y and G are attained for a some intermediate Δx. One can outline two cases: a) moderate-field, moderate-to-strong focusing ($\Delta x < 0$); and b) weak field, maximum focusing ($\Delta x > 0$). To assess the optimal range of Δx and B_y for the case (a) a number of simulations and measurements were made. We used λ_w = 9 mm and g = 4.5 mm to simplify the magnetic field measurements. The yokes of the mock-up were made from soft steel 'Armco' and NdFeB permanent magnets had the remanent field B_r=1.1 T. In the simulation a maximum value of B_y of about 2.68 kGauss is attained for a = 3 mm, b = 0, h = 8 mm, α = 64° and $\Delta x \approx$-0.75 mm. During the mock-up measurements it was obtained B_y=2.56 kGauss for $\Delta x \approx$-1.0 mm. The magnetic field gradient G is equal to 215 T/m for Δx = -1.0 mm and increases to 255 T/m for Δx = 1.0 mm at the peaks of the undulator field and to no less than 210 T/m elsewhere in the vicinity of the Z-axis. For vanadium permendure yokes the computed magnetic field B_y increases up to 2.71 kGauss.

Slightly modified scheme is shown in Fig. 2. PM blocks (2) are removed from the median plane and fixed behind steel yokes (1). Angle γ between a magnetisation vectors of the PM blocks and x-axis is equal to ± 20°. The scheme provides the magnetic field amplitude enhancement up to B_y=3.05 kGauss for the parameters β=0, a=2.2mm, α=80°, Δx=-2.0mm and g=4.5mm, and up to B_y=3.17 kGauss for β=-7°, Δx=-1.8mm and g'=4.72mm, g=4.5mm.

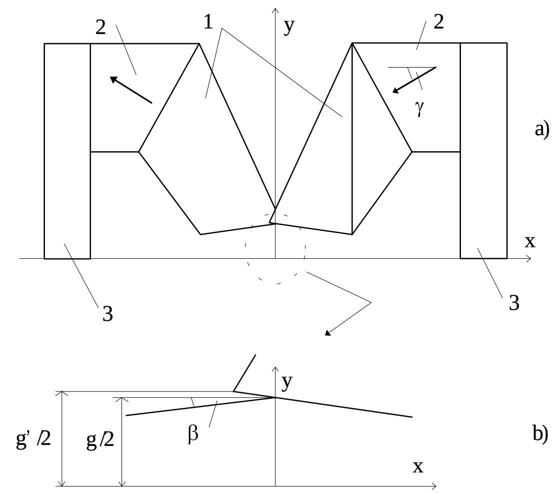

Figure 2. Improved undulator structure: 1 - vanadium-permendure steel yokes; 2 - NdFeB permanent magnets; 3 - steel plates.

An analysis of the simulations and experimental measurements for the case (b) has shown, that there are two primary contributing factors to the high gradient value: the edge magnetic field profile near the pole tips (edges) and the trapezoidal shape of the poles (see Fig. 1, top view). The dominant contribution is the edge field. This part is approximately 75% for Δx = -1.0 mm. The computer simulations [11] predict increased values of both the magnetic field B_y=3.17 kGauss and gradient G = 350 T/m (vanadium permendure was used).

This scheme also allows further gradient enhancement due to the additional PM blocks. One can use, for example, triangular PM blocks (4), as shown in the insert of Fig. 3. If the blocks are magnetised in the horizontal direction, G becomes 450 T/m. When the blocks are magnetised in the vertical direction (topologically equivalent to the «planar-PM» quadrupole [12]), G becomes 495 T/m. With an additional set of planar-PM quadrupole pieces (5) and a steel image plate (2) the magnetic field gradient G can attain a value of 514 T/m. Fig. 3 exhibits the behavior of G in horizontal plane for the last case.

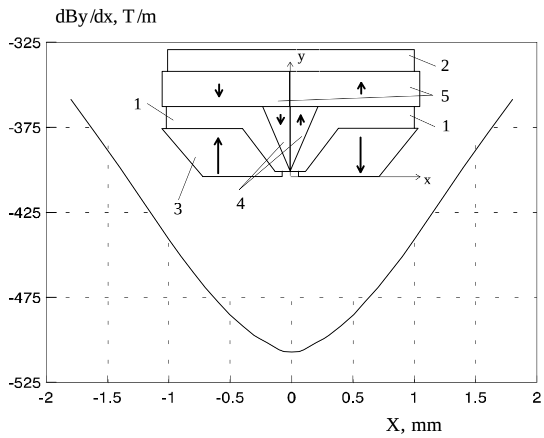

Figure 3. Magnetic field gradient as a function of x-coordinate. a=3 mm, b=0, h=8 mm, α=70°. The insert shows some additional elements which were used in the simulations. 1 - steel yokes; 2 - additional steel plates; 3 - main PM magnets; 4 - PM quadrupole blocks; 5 - additional PM blocks.

4 SUMMARY

We compared the effectiveness of our hybrid quadrupole focusing geometry to the theoretical performance of: 1) the planar-PM geometry [12], 2) a conventional electromagnetic quadrupole, and 3) the Halbach 4-fold rotationally symmetric PM geometry [13]. For the same gap and similar external transverse dimensions scheme [12] can attain a maximum of about 350 T/m, the conventional device about 800 T/m, and Halbach's scheme [13] about 1050 T/m. Thus, our suggested geometry appears capable of attaining a focusing field of more than 50% of the Halbach pure-PM structure. It should be noted that with both the lateral and triangular PM pieces in place, our reported geometry is beginning to approach the 4-fold rotation symmetry of a hybrid/PM quadrupole in the vicinity of the axis. Indeed, if we picture a conventional quadrupole in the x-y plane with thickness $\lambda_w/2$ in the longitudinal direction, we see that a single period of our structure can be approximated by cutting the quad in half along the y axis and $\lambda_w/2$ displacement of the two pieces. Obviously, this procedure will, to first order (i.e., disregarding the effects of pole shape), reduce the gradient of the original quad by about 30% and will simultaneously generate a modest dipole field along the z axis. In this regard, we stress that further practical maximisation of the undulator field of our structure can in all likelihood be achieved with a more detailed optimisation of the (3-D) pole face contours. An additional possibility could involve the development of bias magnets to help concentrate the dipole field components across the mid-plane gap. Although this would appear to violate our goal of avoiding the use of individual small-scale PM pieces, it may in fact be possible to configure bias structures out of machined pieces of monolithic PM material. Our plans for future R&D involve the systematic investigation of these and other approaches, as well as the development of the proposed structure for technical applications.

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