Design of a helical staggered undulator

C H Chang, P H Lin, F Y Lin, C S Chang and C S Hwang

NSRRC, 101 Hsin-Ann Road, Hsinchu Science Park, Hsinchu 30076, Taiwan

E-mail: chang <chang@nsrrc.org.tw>

Abstract. A helical staggered undulator with a short period was designed to generate elliptically polarized photons. To enhance the helical field, cryogenic permanent-magnet blocks were added between the poles in hybrid-type staggered arrays, and a further exotic holmium pole was used in an analysis of the pure-type staggered arrays. A greater helical field strength was achieved with an optimal solenoid field. A helical staggered magnet with rotation of the poles was investigated; the stronger horizontal and vertical fields generated elliptically polarized photons over a much wider range. The spectral performance with elliptical polarization is presented. The field homogeneity and the distribution of the integral field on the transverse axis were calculated. The field performance of a helical staggered structure was examined with a three-period mock-up.

1. Introduction

A helical undulator requires the horizontal field \( B_x \) and the vertical field \( B_y \) to be out of phase in the longitudinal direction. Such an undulator can be designed with up and down magnetic arrays with alternating directions of the rotated poles in the horizontal plane. This concept of rotating the pole to generate the horizontal and vertical fields was suggested by Walker in the ELLETRA laboratory. A helical undulator with a short period can produce elliptically polarized photons with greater energy for a given particle energy, but the achievable field decreases as the ratio of period to gap decreases in a period with a short length. To maintain a reasonable gap and tunability of the photon range, it is necessary to increase the strength of the helical magnetic field; for this purpose, a superconducting helical undulator has been designed [1]. Even though the idea of a superconducting helical undulator is
simple, there exist technical challenges due to image current, radiation heating and the field-error correction to be overcome.

A cryogenic permanent-magnet planar undulator with a short period has been developed at SPring-8 [2]. The cryogenic permanent magnet attained a maximum remanence field 1.58 T when NdFeB permanent magnets were cooled to 150 K. To take advantage of the large-remanence field, a helical staggered undulator was proposed in which a cryogenic permanent magnet is inserted so as to strengthen the magnetic field [3]. Like the superconducting helical undulator, a skim is used with rotated poles to produce elliptically polarized radiation, although the achievable maximum field remains smaller than the superconducting helical undulator at the same gap width. The helical staggered undulator can be designed to operate in vacuum. The achievable minimum gap can be smaller than that of a superconducting undulator. We analyzed a helical staggered undulator with a hybrid structure to generate a stronger helical field and to produce elliptically polarized radiation. Figure 1 is a schematic drawing of the helical staggered undulator. The horizontal and vertical fields vary with the angle of rotation of the magnetic poles. In this work, an optimized magnetic structure was designed to achieve a maximum horizontal field with the helical staggered undulator.

![Schematic drawing of a helical staggered undulator](image)

**Figure 1.** Schematic drawing of a helical staggered undulator

### 2. Performance of the magnetic field for a planar staggered undulator

The first staggered undulator with a short period was constructed for experiments on a free-electron laser (FEL) at Stanford University [4]. This conventional staggered undulator consisted of a solenoid coil and staggered magnet arrays. The pole pieces were constructed from vanadium permendur. Because of the large permeability of such a pole, the solenoid field is deflected vertically into each pole face to form an alternating vertical field, while providing a longitudinal solenoid field. In a staggered hybrid array, the permanent magnet blocks placed between the vanadium permendur poles are arranged to increase the strength of the alternating vertical magnetic field. The direction of magnetization of the magnet blocks should be the reverse of the direction of the solenoid field. To
avert an irreversible demagnetization of the permanent magnet, the solenoid field cannot be operated as a field with flux density exceeding 1.5 T.

We used software package RADIA to construct a model of hybrid staggered arrays and to calculate the expected fields. In this calculation, the cryogenic permanent magnet is NdFeB; the ratio of magnet block to undulator period is 0.4. An optimization of the magnetic structure was performed to achieve a maximum value on varying the solenoid field. In the calculation a pole of length 12 mm and a cryogenic permanent magnet of length 8 mm were assumed, hence a period of length 20 mm and a fixed gap of width 5 mm. The pole material is assumed to be vanadium permendur and the permanent magnet was NdFeB, with a remanent field 1.58 T at cooling temperature 150 K. The longitudinal field of the superconducting solenoid magnet determines the vertical field strength. Figure 2 plots the solenoid field versus vertical fields to optimize the vertical field design. As the magnetization in the pole material is saturated, the achievable maximum fields are 1.45 T at a solenoid field 1.3 T for a hybrid staggered undulator. In comparison with an undulator in vacuum with a period of length 20 mm that is also designed for the storage ring of the Taiwan Photon Source (TPS), the maximum field 1.1 T with a hybrid-type permanent magnet is obtained at the same gap of width 5 mm. The maximum field of the hybrid staggered structure has a 31% greater than that of a conventional hybrid-type permanent-magnet undulator.

![Figure 2. Vertical variation of the maximum field as a function of longitudinal solenoid field in the conventional staggered undulator and the hybrid staggered undulator.](image)

To realize a large magnetic field, we investigated also the use of a holmium pole. For this exotic material holmium, the saturation magnetization at 4.2 K is 3.8 T. The field performance was tested in the superconducting octupole magnet for photon-scattering experiments [5]. A greater solenoid field is required by a superconducting solenoid coil. The magnetization of the permanent magnet must have
become degaussed by the strong reverse field. The holmium pole was employed only in a conventional staggered undulator. According to our calculation of the field, a significantly large field 1.6 T is achieved at solenoid field 3.0 T for a pure staggered structure as shown in figure 2.

3. Magnetic field simulations of a helical staggered undulator

The helical staggered undulator with a short period is designed with a fixed gap to prevent mechanical motion in a vacuum vessel. A schematic drawing of the rotatable configuration is shown in figure 3. The helical undulator produces helical fields through rotation of the poles and magnets in the horizontal plane in alternating directions for the top and bottom arrays. A period of length 20 mm with a pole of length 12 mm and a permanent magnet of length 8 mm at a magnetic gap of width 5 mm was assumed for the field calculation. Table 1 lists the main design parameters of the helical staggered undulator. To avoid degaussing the permanent magnet the solenoid field could not be operated at a field strength exceeding 1.5 T. The longitudinal field 1.3 T is accordingly given to achieve the maximum helical field in the simulations.

| Table 1. Main parameters of the helical staggered undulator |
|-------------------------------------------------------------|
| period length mm   | 28 |
| number of periods | 41 |
| pole material      | vanadium permendur/holmium |
| pole length mm     | 12 |
| pole height mm     | 30 |
| pole width mm      | 60 |
| permanent magnet   | NdFeB |
| PM length mm       | 8  |
| gap height mm      | 5  |
| Rotated angle deg. | 45 |
| $B_z$ solenoid field | 1.3/3 |
| $B_y$ peak field   | T  | 0.9/1.039 |
| $B_x$ peak field   | T  | 0.5/0.613 |

The holmium pole was employed to analyze the helical magnetic field in the pure-type staggered arrays. The pole length of 12 mm and the air space of 8 mm between the poles were kept constant. The vertical and horizontal peak fields were varied with the rotation of the pole about the vertical axis. The undulator period in z-axis is varied by the rotated angle: $\lambda u = \lambda o / \cos \theta$. Figure 4 plots the on-axis horizontal and vertical magnetic fields as functions of angle $\theta$ of rotation of the pole. The optimum angle around 45° may be chosen to produce the horizontal field $B_x$. The on-axis horizontal and vertical magnetic fields achieved up to 0.61 T and 1.039 T on rotation of the pole through angle 45°. A further increase of horizontal field up to 0.82 T and a vertical field 0.9 T were achieved with rotation of the
pole increasing to angle 70°. But, the undulator period is increased up to 58.48 mm at the rotated angle of 70°.

![Figure 3](image)

**Figure 3.** Schematic drawing of the rotated configuration with a constant period of length 28.28 mm.

![Figure 4](image)

**Figure 4.** Horizontal and vertical magnetic fields as functions of angle $\theta$ of rotation of the pole with the period length kept at 28.28 mm and with period length varied by the rotated angle.

To keep the period at the same length, the pole and magnet dimensions in the $z$-direction were varied as a function of angle of rotation. The length of the period was selected a constant at 28.28 mm with the constant ratio of pole length to undulator period of 0.6. Figure 6 indicates the field performance with varied angle of the pole. The figure shows the optimum angle to be 45°, which produces maximum $B_x$; a horizontal field up to 0.61 T and a vertical field 1.093 T were achieved.
Figure 5. Horizontal and vertical magnetic fields as functions of angle $\theta$ of rotation of the pole. The period length was kept constant at 28.28 mm. The maximum horizontal and vertical magnetic fields achieved up to 0.5 and 0.9 T through rotation of the pole by angle 45°.

The helical hybrid staggered structure with constant period length of 28.28 mm was also calculated to analyze the helical magnetic field. Figure 5 plots the horizontal and vertical magnetic fields as functions of angle $\theta$ of rotation of the pole. In each curve, the horizontal peak field achieves up to 0.3 T on rotation of the pole by 45° at solenoid field 1.3 T in the pure staggered structure. Whereas the hybrid staggered structure, the horizontal field $B_x$ increased to 0.5 T and then decreased with increasing rotation angle $\theta$, but the maximum magnetic field $B_y$ decreased from 1.9 T to 0.9 T. The maximum horizontal and vertical magnetic fields achieved up to 0.5 T and 0.9 T on rotation of the pole through angle 45°. The magnetic strength is about 66 % greater than for the pure staggered undulator.

The helical staggered undulator with holmium pole is generated the elliptical polarized radiation. The rate of circular polarization is reduced in the elliptical polarization mode, and the photon flux is smaller than the circular polarization mode in the same energy range. Elliptical polarized photon is calculated using a pure-type helical undulator with a 28.28 mm period length at the pole rotated angle of 45 degrees. Figure 6 displays the photon brilliance calculated for a storage ring of energy 3.0 GeV; the spectral range of the first harmonic elliptically polarized photons can cover from 500 to 2500 eV. The helical staggered undulator might be of interest for the use of circularly polarized photons over a broad spectral range.
Figure 6. Photon brilliance calculated for a 3.0-GeV storage ring; the spectral range of the first harmonic elliptically polarized photons can cover from 500 to 2500 eV.

An anti-symmetric configuration of magnetic array was designed for stringent requirements of an integrated magnetic field. An analysis of the end field was predicted with a three-dimensional calculation. The pole length in the end pole structure was partially adjustable to compensate the field integrals. Figure 7 shows the calculated on-axis vertical and horizontal fields along the longitudinal axis. The field homogeneity of the vertical and horizontal magnetic fields on the transverse axis was calculated. Figure 8 plots the field deviation $\Delta B/B$ within 1% on the transverse axis. The region of effective field is narrow and the roll-off of the field decreases rapidly on the transverse axis. This device favors the use of a shorter region of effective field in the particle machine with a single-pass beam.

Figure 7. Distribution of vertical and horizontal fields along the longitudinal direction, derived from the solenoid field of flux density 3 T.
4. Field measurements of a mock-up

A solenoid coil of length 270 mm with a bore diameter 72 mm made from a hollow conductor of copper provided a solenoid field 0.37 T at exciting current 180 A. A uniformity within 1 % of the longitudinal field was measured in the 100-mm central region of the solenoid coil. A three-period helical staggered mock-up with period 20 mm and rotation angle 60° was fabricated to test the circular field performance. The pole pieces of width 57 mm and thickness 12 mm were constructed from vanadium permendur. Available NdFeB magnet blocks of width 40 mm and thickness 7 mm were inserted between the pole pieces. The field distributions were simulated at rotation angle 60° as shown in figure 9. A nearly identical horizontal and vertical field was generated with 40-mm period length. The field profiles were measured with a three-axis Hall probe system (SENIS x-H3x_E3A) moved with a stepper motor through the bore of the undulator at room temperature. The reproducibility of the Hall probe system was tested within ± 0.5 mT. Figure 9 indicates the measured profiles of the vertical and horizontal fields along the longitudinal direction at gap width 6 mm. The vertical peak field of 0.48 T and horizontal peak field of -0.44 T with a period length of 40 mm were measured at solenoid field 0.37 T, as predicted with the field calculation. The vertical, horizontal and longitudinal profiles along the longitudinal field without operating the solenoid field were also measured as shown in figure 9. The vertical field and horizontal fields, 0.2 and 0.1 T respectively, were produced with permanent magnets. Herein, a three-period mock-up was tested, yielding an experimental confirmation that the helical staggered undulator with circularly polarized mode was achievable.

Figure 8. Field deviation $\Delta B/B$ within 1 % on the transverse axis.
Figure 9. Measured field profiles plotted along the longitudinal axis in the hybrid staggered mock-up. Nearly equal $B_x$ and $B_y = 0.45$ T at central pole were measured for rotation by angle 60°.

5. Conclusion

A hybrid staggered undulator with a short period was designed and optimized to achieve a maximum helical peak field under an optimal solenoid longitudinal field. A notably greater helical magnetic field was achieved on adding a cryogenic permanent magnet. A further increase of horizontal field to 0.613 T was achieved with a holmium pole in the pure staggered structure. The field profiles were measured on a three-period mock-up with gap 6 mm to confirm the helical design. Materials of two types promise a considerably enhanced helical undulator performance. The principal advantage of such a helical staggered undulator is that it can deliver elliptically polarized photons over a much wider spectral range. This work is expected to develop an undulator prototype for testing the performance in the future TPS project.

This work was supported by the National Science Council of Taiwan under No. NSC96-2221-E-218-MY3.

6. References

[1] C S Hwang and P H Lin 2004 Phys. Rev. Special Topics- Accel. & Beam 7 90701
[2] T Hara, T Tanaka, H Kitamura, T Bizen, X Mar‘echal, T Seike, T Kohda and Y Matsuura 2004 Phys. Rev. Special Topics-Accel. & Beams 7 05702
[3] S Sasaki, “The possibility for a short-period hybrid staggered undulator” Proc. 2005 Particle Accelerator Conf., Knoxville, TE USA 982-984
[4] Huang, Y C Wang, H C Pentell and R H Feinstein 1994 Nucl. Instrum. Methods Phys. Res. A.
341 431-435

[5] C S Hwang, C.T. Chen, C.H. Chang, C.Y. Liu, F.Y. Lin, B. Wang, R. Wahrer 2002 *J. Magn. Magn. Mater* **239** 586-590.