Planar Helical Undulator Sources of Circularly Polarized X-rays*

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Abstract

The planar helical undulator is a charged particle accelerator insertion device that produces a helical magnetic field using only planar magnet arrays. The helical field causes the particles to execute helical trajectories, and to emit x-rays with a degree of circular polarization. To switch the x-ray helicity, some designs require a mechanical shift of the magnet arrays. Other designs use a chicane, a separate undulator to produce each polarization, and a chopper to switch between them. We present an analysis of the different magnetic designs that have been proposed, with emphasis on a device for the 500-1000 eV x-ray range on the SPEAR storage ring.

I. INTRODUCTION

There is an increasing demand for circularly polarized soft x-rays in the study of magnetic materials, biological molecules, and other systems that exhibit circular dichroism. At present, most experiments have been done with bending magnet radiation, which is elliptically polarized above and below the horizontal midplane of the storage ring. Insertion devices such as undulators and wigglers have been used to date mostly as sources of linearly polarized radiation. They yield much more intense radiation than bending magnets, so there is an apparent need for insertion device sources of elliptically polarized x-rays.

A number of insertion devices generate elliptically polarized x-rays, such as bifilar solenoids, elliptical and asymmetric wigglers, crossed undulators, and planar helical undulators. [1] We have chosen to study the pure permanent magnet planar helical undulator, which was pioneered by Elleaume at ESRF where he has installed a device of this type called 'Helios'. [2] Diviacco and Walker [3] and Sasaki [4] have developed alternative planar helical undulators; our study is an attempt to compare the different designs.

One class of planar helical undulators involves a chicane and a pair of in-line undulators as in the Helios design. One undulator creates left circularly polarized (LCP) light and one creates right circularly polarized (RCP) light. The chicane strategy creates two beams simultaneously, which both pass through the monochromator. They may be chopped alternately, to give the user only RCP or LCP light at any time. Each undulator is shorter than half of the available insertion region, because of the need to leave space for chicane magnets.

The other class of sources is the single undulator without chicane. Some designs of this type of source can be shifted from RCP to LCP, and it has only one beam through the monochromator. The alternation of polarization would be lower than with a chopper, and might interact with the electron beam, but it would use the center, and not the two horizontal edges of the monochromator optics. This strategy would have more than twice the flux of the corresponding chicane design, both because more periods are used, and because the peak width is inversely proportional to the number of periods.

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II. PLANAR HELICAL UNDULATOR DESIGNS

All of the devices discussed here have four rows of magnets, one in each quadrant surrounding the beam axis. Some of the magnets are used to generate horizontal fields, and some generate vertical fields. Critical parameters include flux, polarization rate, switching convenience between RCP and LCP, and mechanical complexity.

The Helios device of Elleaume is one which employs a standard Halbach jaw (both bottom rows the same) and another jaw that consists of two standard Halbach rows phased longitudinally apart by 1/2 period. [5] The Helios device is mechanically complicated, because its jaw motions are not symmetrical. It creates horizontal fields with one jaw, and vertical fields with the other; in order to generate a circular helix, the half gaps between axis and jaw must be changed separately. The jaws may also be moved longitudinally with respect to each other to change helicity or they could be fixed in phase in a chicane design with two undulators. This device is shown in figure 1:

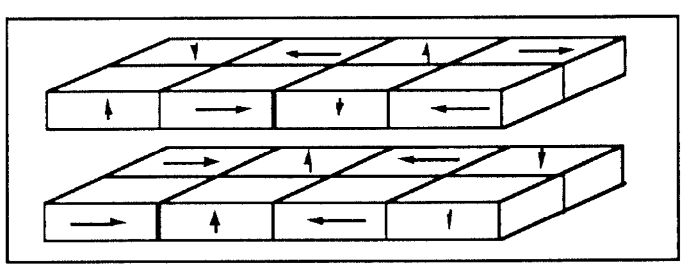

Figure 1: The Helios device, with arrows showing the direction of the easy axis of magnetization in each block.

The design of Walker and Diviacco is like four standard Halbach rows, but instead of blocks with magnetization parallel to the beam axis, those blocks have transverse magnetization The horizontal and vertical fields are equal in strength at any value of gap, so it does not require any phase adjustment. This device cannot be phase shifted to reverse the helicity, so it would not be usable as a single device to generate both RCP and LCP x-rays. To generate x-rays of the opposite helicity to those created by the device in figure 2, one would have to reverse the direction of magnetization of the vertically or the transversely oriented blocks.

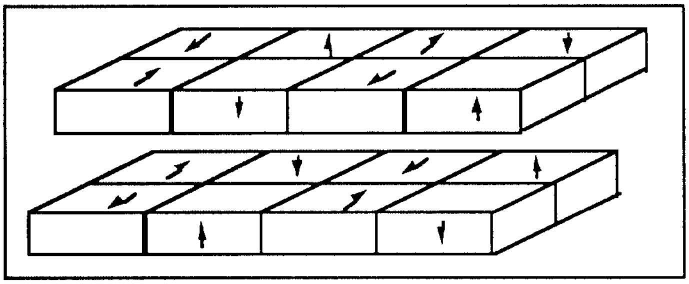

Figure 2: The device of Walker and Diviacco; blocks with vertical arrows create horizontal transverse fields; blocks with horizontal arrows create vertical fields.

The Sasaki device consists of four standard Halbach rows, but two of the rows must be phase adjustable in order to maintain a circular helix. Two rows, (say upper left and lower right) are moved together with respect to the fixed rows, but by a rather small amount (.13 to .18 period) to maintain a circular helix. By switching the phase though zero, the opposite sense of polarization is obtained. This geometry is shown in figure 3:

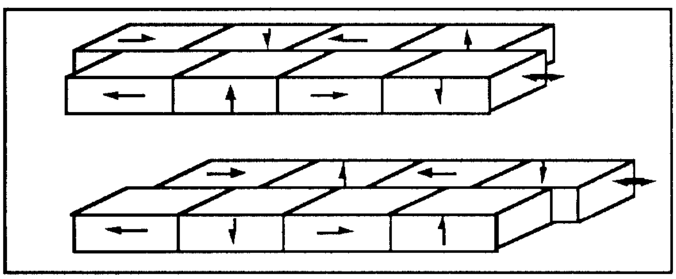

Figure 3: The Sasaki design; the lower front, and upper back rows are fixed and aligned; the lower back row and the upper front row are shifted to the right.

We are currently building a device starting with the Sasaki concept, but with the further extension that all four of the cassettes are moveable longitudinally. This will allow us to create vertically, circularly, and horizontally polarized radiation. In addition, we will be able to change the characteristic energy of the radiation by moving the top jaw longitudinally with respect to the bottom jaw or by moving the rear pair of cassettes with respect to the front pair. Such motions maintain ellipticity according to the way the original Sasaki phase is set, but they change the magnitudes of the magnetic fields, with no need to change the gap, as with the linearly polarizing adjustable phase undulator [6]

III COMPARISON OF DESIGNS

We modeled these devices using a program based on finite element decomposition of magnet blocks. For a circular helix, the field strengths must be equal, and the fields must be 90^o apart in phase. We consider only pure permanent magnet devices where the magnet blocks have square cross section; this generates almost all the field strength that could be obtained from blocks of greater height. We consider the blocks to be 'wide' in the transverse direction, so that we do not suffer from finite width effects.

In designing an undulator for a given energy range, it is useful to study the following plots of B field versus period length, which are derived from the equations: [7]

$$E_f = \frac{950\, E_e^2\,(\mathrm{GeV})}{\lambda\left(1 + K^2/2 + \theta^2\gamma^2\right)} \qquad [1a]$$

$$K = .934\, B(T)\, \lambda\,(\mathrm{cm}), \qquad B = \sqrt{B_x^2 + B_y^2} \qquad [1b]$$

For circular polarization, $B_x = B_y$, so that $B = \sqrt{2}\, B_{x,y}$.

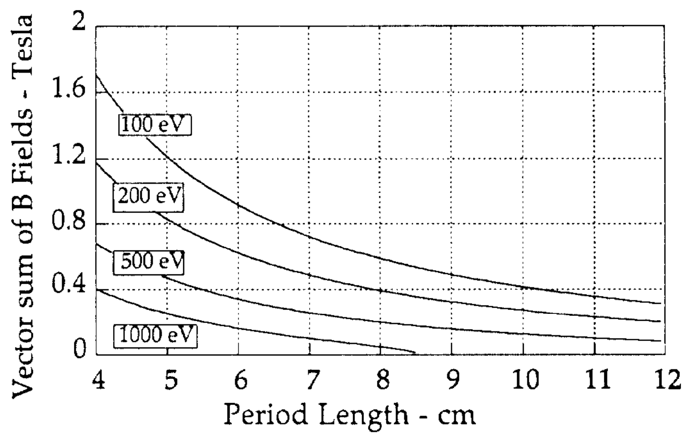

Figure 4: B field as a function of period to create x-rays of various fundamental energies with a 3 GeV electron beam.

The table below shows the calculated characteristics of various undulator designs, based on a minimum energy of 500 eV.

Undulator Type	Period Length	K Parameter	Number of Periods	P1 Flux Watts/ 100mA
Halbach Single	6.9	1.72	27	7.95
Elleaume Single	7.6	1.57	24	5.32
Elleaume Chicane	7.6	1.57	10	2.22
Walker Chicane	7.4	1.67	10	2.58
Sasaki Single	6.5	1.79	28	9.49
Sasaki Chicane	6.5	1.79	11	3.73

Table 1: The values were based on computations of B fields from the modeling program, and period lengths from Figure 6.

The undulator calculations assumed $B_r = 1.2$ T NdFeB magnets of square cross section and 60 mm width, with a gap of 30 mm. The total length of 'single' devices is

1.9 m. and for the 'chicane' geometries, we use 1.5 m as the length available for the undulators. The Halbach linearly polarizing device is included for comparison. Flux was calculated for the power in the first harmonic: [7]

$$P_1 = \frac{\pi\, c\, I\, e\, N\, Z_0\, g^2\, K^2}{3\,\lambda_u\left(1 + \left(K_x^2 + K_y^2\right)/2\right)^2} \qquad [2]$$

N is the number of periods, and I is the electron current. Note that the single Sasaki device produces 19% more flux than a single Halbach device. This may be thought of as a consequence of the fact that the electrons are being accelerated continuously in a helical path, but only sinusoidally in a planar oscillating trajectory. The plot below shows the flux integrated over the undulators' central cones: [8]

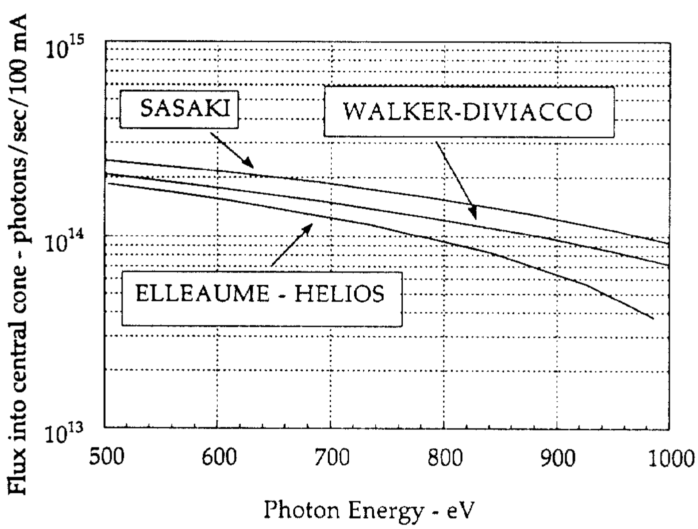

Figure 5: Central cone flux compared for 2 meter devices on SPEAR, with 100 mA electron beams.

IV: DISCUSSION

For an ideal electron beam, the flux from all of the planar helical undulators with circular helical orbits is 100% circularly polarized. A bending magnet or wiggler does not yield appreciable flux with more than about 90% circular polarization.

From flux considerations, it would appear that a single Sasaki type device would be preferred. Not only is the flux in the fundamental peak higher even than the comparable Halbach device, but the peak is narrower than all the other circularly polarizing devices because of the greater number of periods. From our experience on the adjustable phase undulator [6] it appears that the phase of an undulator may be changed with negligible disruption of the electron beam, so both directions of polarization would be available, with a slewing time of a few seconds between directions.

In the Walker-Diviacco design, the helicity of the electron trajectory remains exactly circular, independent of gap. This is convenient in that it does not require phase motion, but it does not allow the user to generate elliptical polarization, which may be useful. Elliptical polarization may be needed to overcome ellipticity in the optics, or to overcome ellipticity which occurs when the electron beam is off axis. Also, since its helicity cannot be changed by phase shifting, its use would be limited to a chicane geometry if both directions of circular polarization were desired.

The Elleaume design is more complicated mechanically, and has less flux than the other two designs. Also, with separate half gap adjustments for each jaw, one would have to move the undulator magnets separately from the chicane magnets. The Sasaki device can be phase shifted so that it produces linearly polarized light in the horizontal (phase = 0) or vertical direction (phase = 1/2 period). The Elleaume device can also be phase adjusted to produce linearly polarized light, but in the ± 45^{0} directions.

The first choice is between the chicane and single undulator strategies. The single undulator uses the monochromator optics in a simple way, gives much more flux, and requires no chicane magnets, but is limited with regard to helicity switching. The chicane strategy would allow rapid switching with no disturbance to the electron beam, but makes more demands on monochromator optics, has much less flux, and requires effort in the design of the chicane. If a chicane strategy is adopted, the Walker strategy allows phase to be fixed for all gap settings; if the Sasaki phase is fixed, the polarization would be somewhat elliptical.

A problem common to all of the 4 cassette planar helical undulators is that their horizontal fields have a narrow horizontal profile. The vertical field can have a broad profile, proportional to the transverse width of the magnets. But the narrow horizontal field profile is a consequence of the sharp discontinuity between the parallel cassettes. This creates the requirement that the electron beam be steered accurately down the axis of the undulator. The x-ray spectrum will be blue shifted if the beam is horizontally off-axis.

V: REFERENCES

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[8] The author thanks Steve Lidia of LBL for this data.