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COMPARISON OF PLANAR HELICAL UNDULATOR DESIGNS FOR SPEAR BEAMLINE FIVE*

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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 that is circularly polarized above and below the horizontal midplane of the storage ring. 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]

Elliptically polarized light is generated when electrons enter a helical magnetic field; the helicity of the field determines the helicity of the x-ray emission. Among the various technologies, the pure permanent magnet planar helical undulator is probably the best choice for installation on BLV in summer, 1993. This approach was pioneered by Pascal Elleaume at ESRF; he has installed a device of this type called 'Helios'. [2] Richard Walker [3] and Shigemi Sasaki [4] have developed alternative planar helical undulators, which improve on the basic design of Elleaume. This proposal is a discussion of planar helical undulator strategies from which implementation choices can be made. We will consider only pure RCP and LCP sources, since we are trying only to span the range from 500 - 1000 eV. If we needed a broader range, we might consider creating elliptically polarized light, and hence, harmonics which RCP and LCP sources do not have.

Strategy

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 could diverge by as much as 1.7 mrad on beamline 5; this is determined by the width of the grating holders. Both beams would pass through the beamline 5 monochromator. They would then be chopped alternately by a mechanical chopper, so as to give the user only RCP or LCP light at any time. Each undulator would be shorter than half of the available insertion region, because of the need to leave space for chicane

magnets. The short length generates less monochromatic flux, both because fewer periods are used, and because the peak width is inversely proportional to the number of periods.

The chicane strategies would require at least one bending magnet between the two undulators (a 1 kG 10 cm magnet would generate a 1 mr bend), and, if the trim compensation coils were not suitable for the other bends, three bending magnets would be required. The use of three magnets is probably required in any case, since they could be used to create flux return paths for each other; the two on the ends would return the flux from the central one by means of an iron bar between them. Such a strategy would be required to accommodate the other undulators on the beamline 5 multiundulator. Figure 1 shows the design schematically:

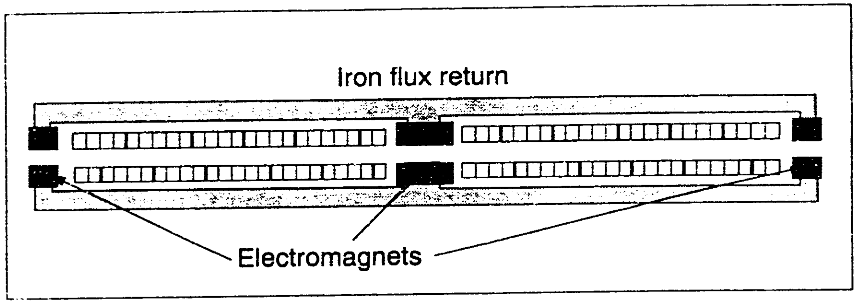

Figure 1: Schematic side view of possible chicane strategy compatible with the beamline 5 multiundulator.

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 slower, and might interact with the electron beam, but it would use the center, and not the edges of the monochromator optics. This strategy would have more than twice the flux of the corresponding chicane design

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. Sasaki has built a device with 45° magnetization, but its field strength is inferior to his 90° design. The 45° device is a short prototype, but he is building a full scale 90° device for Spring-8; he has raised the possibility that this device might be loaned to SSRL for testing.

Selection criteria among the choices will include flux, polarization rate, and switching convenience between RCP and LCP. The device should span the 500-1000 eV range., and should have reasonable mechanical simplicity. In this range, we would employ a monochromator diffraction grating with a 2° angle of incidence, which is small enough to pass circularly polarized

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light without much elliptical distortion. Polarization rate depends on the ellipticity of the orbit; all the choices can produce circular helices.

Devices

To begin the description of the devices, we first show a standard Halbach device, [5] but split it longitudinally to show the orientation of the 4 rows of magnets found in all the other devices:

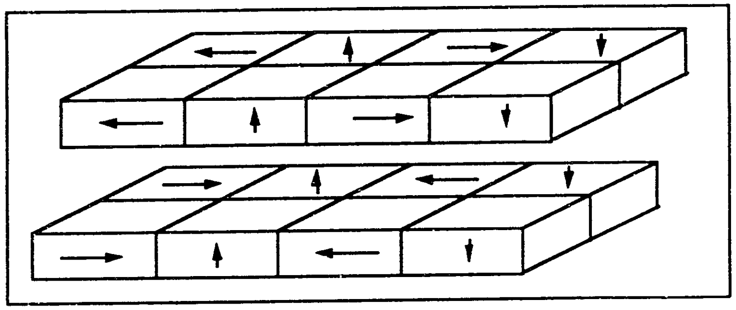

Figure 2: Split Halbach undulator, with arrows showing the direction of magnetization in each block.

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. The two rows in the split jaw do not move with respect to each other. The lower and upper jaws are moved in phase with respect to each other to change the polarization, which is independent of gap. 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 generated separately. The jaws may also be moved in longitudinal phase to change helicity or they could be fixed in phase in a chicane design with two undulators. This device is shown in figure 3:

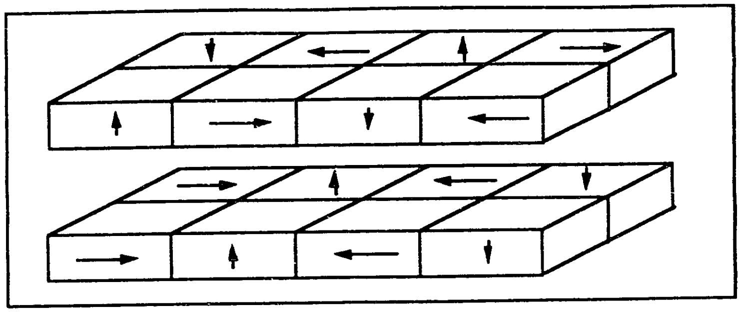

Figure 3: Elleaume's Helios device showing standard full width Halbach jaw below, with jaw to create horizontal fields above.

The Walker device is like four standard Halbach rows, but instead of blocks with magnetization parallel to the beam axis, those blocks have magnetization transverse to the beam axis. The geometry is shown in figure 4:

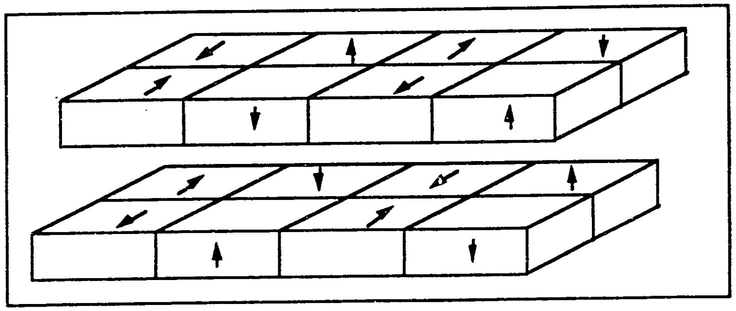

Figure 4: The device of Walker and Diviacco; blocks with vertical arrows create horizontal transverse fields; blocks with horizontal arrows create vertical fields.

An advantage of the Walker device is that its horizontal and vertical fields are equal in strength at any value of gap, so it does not require any phase adjustment. The Walker 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 4, one would reverse the direction of magnetization of the vertically or the transversely oriented blocks.

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. These 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 5:

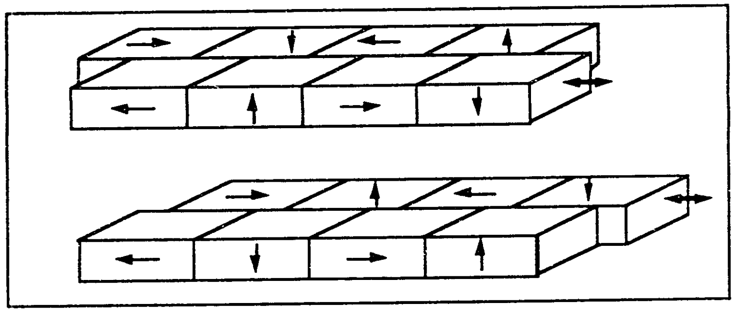

Figure 5: The Sasaki design; the lower front, and upper back rows are fixed and aligned; the lower back row and the upper front row are shifted to the right.

The mechanical design of a Sasaki device is shown schematically in figure 6:

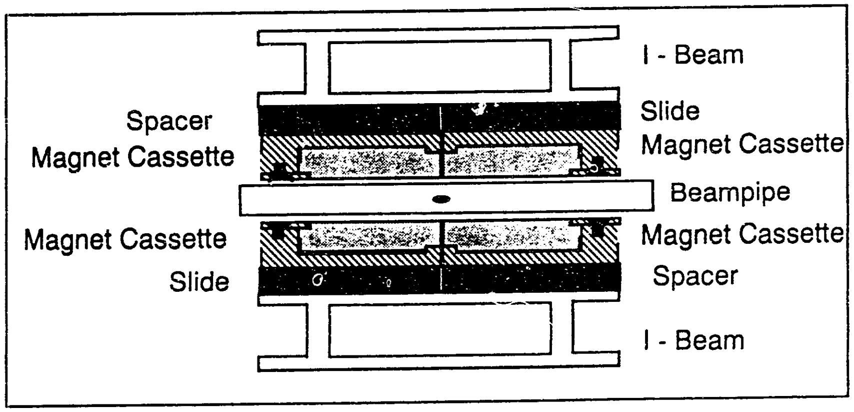

Figure 6: End view of a Sasaki type undulator. The I beams are structural supports attached to the beamline 5 undulator mover. The magnet cassettes in the upper right and lower left quadrants are mounted on slides. It may be preferable to mount the magnets directly onto separate 'I' beams, and then to mount the 'I' beams on slides.

If the phase of the Sasaki device were fixed, at say .155 period, it would give elliptically polarized light, with ellipticity of .8 to 1.2. over the 500 - 1000 eV range. The benefit of fixing the phase in a chicane configuration is that one could simply chop the radiation without doing anything that would possibly interfere with the electron beam. One could also fix the phase at other values nearer those of a given experiment, so as to obtain even less ellipticity.

Comparison

I wrote a computer program (XCPU and variations) to compute the magnetic fields of any planar helical device. It is based on a finite element decomposition of magnet blocks. Its output is a graph of the vertical and horizontal fields for a five period device. For a circular helix, the field strengths must be equal, and the fields must be 90° apart in phase. We consider only pure permanent magnet devices, since hybrids are more complex to model. We also consider the case 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 case where the blocks are 'wide' in the transverse direction, so that we do not suffer from finite width effects.

In designing an undulator capable of spanning the range from 500 to 1000 eV, it is useful to study the following plots of B field versus period length, which are derived from the equations:

1a $E_f = \dfrac{950\, E_e^2\,(\mathrm{GeV})}{\lambda\left(1 + K^2/2\right)}$

1b $K = .934\, B(T)\, \lambda\,(\mathrm{cm})$

1c $B = \sqrt{B_x^2 + B_y^2}$

In the case of circular polarization, $B_x = B_y$, so that $B = \sqrt{2}\, B_{x,y}$.

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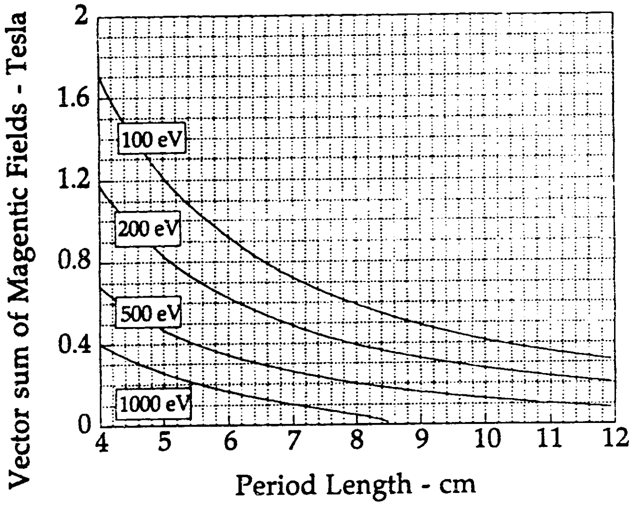

Figure 7: B field as a function of period to create x-rays of various fundamental energies. As an example, an undulator with a 7 cm period would have to generate a field of 0.23 T to create 500 eV x-rays, and 0.13 T to create 1000 eV x-rays.

The table below shows the calculated characteristics of various competitive undulator designs:

Undulator Type	Period Length	Kincaid Parameter	Number of Periods	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, at the minimum fundamental energy of 500 eV 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. All of the devices would be tuned to 1000 eV by moving to a larger gap. The Halbach device is included for comparison, though it

produces only linearly polarized light. Flux was calculated from the formulas for the power in the first harmonic and total power:

$$\text{2a} \quad P_1 = \frac{P_T}{(1 + K^2/2)^2}$$

$$\text{2b} \quad P_T = \frac{\pi c I e N Z_o \gamma^2 K^2}{3 \lambda_u} = 0.76\, E_e^2\,(\text{GeV})\; K^2\; N\; I\,(\text{A})\; / \;\lambda_u\,(\text{cm})$$

$$\text{2c} \quad K = \sqrt{K_x^2 + K_y^2}$$

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.

An installation on beamline 5 should have significantly greater flux than what is available from bending magnet beamline 8, for the project to make sense. Beamline 8 delivers about 50-100% of the total flux delivered by beamline 5 at 800 eV, which is about 4 x 10^9 photons/sec/100 mA. The flux from all of the planar helical undulators with circular helical orbits is more than 90% circularly polarized, and one fourth of the beamline 8 flux is more than 90% circularly polarized. At the present time, beamline 5's flux is much less than predicted theoretically, mostly because of a broadening of the fundamental in the 500-1000 eV range. If this problem could be solved, there would be a very substantial gain on beamline 5; perhaps an order of magnitude. A full scale Sasaki device on beamline 5 will produce at least 5-10 times the 90% polarized flux available from beamline 8.

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 on beamline 5, [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. There may also be some administrative control over how often a switch might be done, and over whether the user would be allowed to control the switching, at least at the beginning.

A feature of the Walker design is that the helicity of the orbit remains exactly circular, independent of gap, unlike the Sasaki design. This is convenient in that it does not requrie 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. The Walker design is marginal in range; if it has the period indicated in the table, it would have negligible flux at 1000 eV. 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. It would not span the full range from 500 to 1000 eV; if it could go down to 500 eV, its first harmonic would not go to 1000 eV. Also, with separate half gap adjustments for each jaw, one would have to move the permanent 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 Walker device is not phase adjustable and cannot be made to yield linearly polarized light.

Conclusion

The first choice is between the chicane and single undulator strategies. The single strategy uses the monochromator optics in a simple way, gives much more flux, requires no tricky chicane magnets, but is more 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 considerable effort in the design of the chicane magnets.

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. If the Sasaki phase is variable, it is more complicated mechanically; a total of 4 magnet cassettes would have to be mounted on slides.

At a meeting on November 11, 1992, the consensus of the SSRL users is that they would prefer flux over rapid switching, though they do want switchability; this argues for the single undulator Sasaki design.

At present, the minimum gap allowed on beamline 5 is 32 mm, though the beampipe itself is a 1" pipe with another millimeter or two of twist. We have verified that a minimum gap of 30 mm is allowable. This would allow all of the circularly polarizing devices to generate stronger maximum fields.

The standard magnet material used in undulators like Sasaki's test device is a material (Shin -Etsu's N33H) which has a B_r of about 1.1 T. There is a newer material, Shin - Etsu's N42, which has a B_r of about 1.3 T and which may be preferred for its additonal strength. These materials must be derated somewhat because thermal stabilization (at 60C) and magnetic stabilization (putting them in a demagnetizing field of 110 - 120% of H_c) causes them to lose some B_r. In any case, we could probably plan having a material with a remanent field of 1.2 T

A problem common to all of the 4 cassette planar helical undulators is that their horizontal fields have a narrow profile in the horizontal. The vertical field can be made to have a broad field 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 a requirement that the electron beam be steered accurately down the center of the undulator. It will also lead to a blue shift of the x-ray spectrum if the beam is horizontally off-axis.

We also may wish to refine our energy range somewhat, to bracket the first row transition elements of magnetic interest. The chromium 2p3/2 edge is at 575 eV and the copper 2p1/2 edge is at 952 eV. Thus a 550 - 950 eV range may be the most useful one.

The beamline 5 monochromator, using the 2 degree grating, passes appreciable radiation even at 1400 eV; this might argue for an elliptically polarizing device which could create third harmonic light, but a strong experimental case should be made for such a design requirement. Adjustable phase Sasaki and Elleaume devices can produce elliptically polarized light on axis.

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