Advanced Insertion Devices

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Abstract

Various schemes for extending the performance of insertion devices are reviewed. Particular emphasis is given to recently developed structures for generating elliptically polarized radiation.

1. INTRODUCTION

More than fifty insertion devices (IDs) are presently in operation in synchrotron radiation sources world-wide and the number is increasing rapidly with the coming into operation of the latest generation of synchrotron radiation sources. Like the storage rings themselves IDs have undergone considerable development since the earliest devices, both in terms of magnetic field quality and complexity of design. Better quality has been demanded to minimize effects on the electron beam and improve radiation performance. The developments that will be discussed here concern complexity i.e. concepts that extend the range of possibilities offered by the standard devices, both for the present and the next generation of synchrotron radiation source [1].

We define a standard device to be an undulator or wiggler with linear polarization where the transverse field components may be written as : $B_x = 0$; $B_y = B_o \cos(kz)$, where $k = 2\pi/\lambda_o$. Such a device is usually constructed using either electromagnet, normal or superconducting (SC), or permanent magnet, pure permanent magnet (PPM) or hybrid (HYB), technology. For further information the reader is referred to various review articles [2-7].

2. LINEARLY POLARIZED DEVICES

2.1 *Anti-symmetric and no-steering configurations*

An insertion device is required to produce no net change in angle ($\Delta x'$) or position (Δx) of the beam. Referred to the centre of the device (z=0), the changes are given in terms of the following field integrals :

$$\Delta x' = \frac{e}{\gamma mc}\int B_y\, dz \qquad \Delta x = -\frac{e}{\gamma mc}\int zB_y\, dz$$

The most common solution is a field distribution that is symmetric in the z-direction and so from the above, $\Delta x = 0$. The condition $\Delta x' = 0$ is obtained by correct setting of the outer poles, in the simplest case using half-strength poles i.e. a pole sequence 1, -2, 2, -2, 1. An alternative is the anti-symmetric configuration, for which $\Delta x' = 0$ automatically and $\Delta x = 0$ is achieved by end-pole adjustment. The advantage of this arrangement is that an imperfect cancellation of the field integrals, for example at different gap settings, produces a change in position and not angle, which the closed orbit is generally less sensitive to. There is also a cancellation of systematic multipole field errors. For this reason several IDs have been constructed with an anti-symmetric configuration, for example at DESY [8] and ESRF.

Even with perfect field integral cancellation there remains an offset of the beam oscillation axis in either position

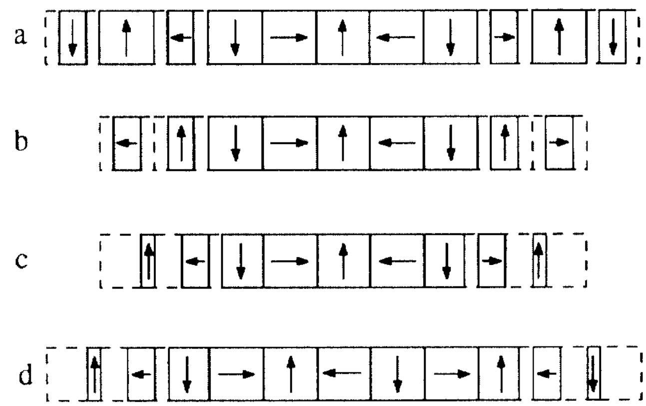

Figure 1. No-steering permanent magnet configurations.

(symmetric case) or angle (anti-symmetric case) with respect to the nominal axis, which can be of importance in some applications. "No-steering" configurations which eliminate this offset have therefore been developed. The simplest sequence of (equi-spaced) pole strengths that achieves this is 1:3:4 which can be used in either a symmetric (1,-3,4,-4,4,-3,1) or anti-symmetric (1,-3,4,-4,4,-3,1) arrangement. Fig. 1 shows some PPM schemes that achieve the same effect, whose solution is based on the linear superposition of the field from individual blocks. Figs. 1a and 1b use only half-blocks [9], while fig. 1c is based on a sequence of 1/4, 1/2, and 3/4 size blocks. Any of these can be made into an anti-symmetric configuration, as shown for example in fig. 1d.

2.2 *Adjustable phase devices*

The standard permanent magnet ID relies on a change of gap between the magnet arrays to change the field strength. An alternative method is to shift one magnet array with respect to the other along the beam direction [10]. The adjustable phase ID has the advantage of being mechanically more simple than the adjustable gap version. It also has the property that the vertical focusing effect remains constant, independent of the phase. A potential disadvantage is the fact that when the field strength is close to its minimum value there is a linear variation of the vertical field component with vertical position, making the output wavelength sensitive to beam position [11]. In the fully nulled case the field variation is given in the 2D limit by $(dB/B)/dy = k$, e.g. 9 % per mm for a 70 mm period device. This can also give rise to a broadening of the spectrum in cases where the vertical emittance is large. A full non-linear beam dynamics simulation, of the type carried out for conventional IDs, has not yet been carried out for the adjustable phase device, however tests of a device on SPEAR have shown minimal effects on the electron beam [12]. The adjustable phase concept has also been applied to a PPM elliptically polarized device (see 3.3 below). The possibility of using hybrid structures has not yet been considered.

3. ELLIPTICALLY POLARIZED DEVICES

3.1 Introduction

One of the areas of ID development that has seen the greatest activity in recent years is that of devices for producing circular, or in general elliptical, polarization [13]. An International Workshop was recently organized on this specific topic [14]. Generally we may divide ID sources of polarized radiation into 3 categories :

i/ Wigglers with an asymmetric field distribution, producing elliptically polarized radiation vertically off-axis, as in a bending magnet [15]. A pure-permanent magnet device of this kind was built at HASYLAB [16] and subsequently hybrid devices have been built at HASYLAB, LURE and ESRF. The possibility exists of varying the vertical angle of the electron beam in the device to switch the helicity of the radiation received on-axis, but so far this has not been attempted.

ii/ Undulators with separate horizontal and vertical polarization, producing elliptically polarized radiation on-axis through an interference effect, the so-called "crossed undulator" [17]. In this case it is possible to alter the polarization by varying the difference in radiation phase between the two undulators using a "modulator" magnet. The first, and so far only, device of this type was installed in BESSY in 1990 [18]. The present modulator is not laminated and so does not permit fast switching; the user measures a spectrum with one helicity, then switches it and measures the spectrum again. With a suitable design of magnet a switching rate of at least 10 Hz should be achievable [19].

iii/ Undulators or wigglers with elliptical electron trajectories which produce elliptically polarized radiation on-axis. The various possibilities are considered below, distinguishing between devices with a helical or planar geometry.

3.2 Helical devices

The "classical" device consists of a set of helical current windings; the use of two sets of windings would allow arbitrary polarization to be produced [20]. A helical arrangement of permanent magnets [21] or electromagnets [22] is also possible. In these devices the helicity is fixed by the mechanical structure. The elliptical undulator is a more flexible arrangement consisting of superimposed horizontally and vertically polarized undulators which can produce arbitrarily polarized radiation depending on the field strength and the relative phase of the two magnet arrays [23]. A device of this kind has been tested in the TERAS ring in Japan [24].

The elliptical wiggler [25] is similar to the elliptical undulator except that the vertical field component is a strong wiggler field (K > 10), while the weak horizontal field (K ~ 1), 90^{o} out of phase, serves to give a different vertical deflection angle to the radiation from the positive and negative poles and so produce elliptically polarized radiation on-axis. Two devices of this kind are in operation [26]. Using an electromagnet to generate the weaker field component allows the helicity to be rapidly inverted. Electromagnetic Elliptical Wigglers have been proposed for ELETTRA [27] and are under construction at the ALS [28], and by a NSLS/APS/NPI collaboration [29]. Table 1 gives the main parameters of these devices. In the case of the ELETTRA device it is also intended to operate in an undulator mode, producing radiation with a photon energy as low as 5 eV ($K_x = K_y \approx 1$).

Table 1
Main parameters of proposed Electromagnetic Elliptical Wigglers; period length (m), no. periods, max. K_x, max. vert. field (T), critical energy and photon energy range (keV).

λ_o	N	K_x	B_y	ε_c	ε_{min}-ε_{max}	Type	Ring
0.2	13	1.5	2.0	3.0	0.05-10.0	HYB	ALS
0.23	12	1.0	0.6	0.9	0.005-1.2	PPM	ELETTRA
0.16	5	1.5	0.8	3.3	1.0-10.0	HYB	NSLS

3.3 Planar devices

Recently a number of new designs have been produced that eliminates one of the main disadvantages of the above helical structures, namely that the strength is limited by both the horizontal and vertical magnet gap. In these planar designs the performance is limited only by the vertical gap, as in a conventional ID [30].

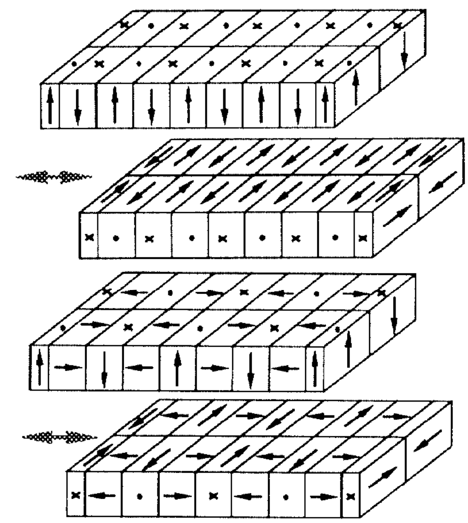

Figure 2. Planar helical devices (a) HELIOS-I, (b) HELIOS-II

The first device of this type to be proposed, HELIOS, is shown in fig. 2 [31]. In each of the two versions the upper magnet array produces a periodic horizontal field component, while the lower array produces a vertical field. The lower array can be shifted with respect to the upper by a distance D, and hence phase $\phi = 2\pi/D$. The field components on-axis are the same as for the elliptical undulator and can be written as :

$$B_x = B_{xo}\cos(kz)$$

$$B_y = B_{yo}\cos(kz+\phi)$$

The output wavelength is independent of ϕ and is in general varied by altering B_{xo} and B_{yo} i.e. by adjusting separately the half-gaps of the upper and lower arrays.

The polarization of the radiation is usually described in terms of the Stokes' parameters, which in the low K-value limit are given as follows :

$$S_1 \sim B_{xo}^2 - B_{yo}^2 \quad S_2 \sim 2B_{xo}B_{yo}\cos\phi \quad S_3 \sim 2B_{xo}B_{yo}\sin\phi$$

from which it can be seen that in general all three components are non-zero. In the helical mode ($B_{xo}=B_{yo}$) the radiation varies between polarized linearly at 45^{o} ($\phi=0$), right circularly polarized ($\phi=\pi/2$), linear at -45° ($\phi=\pi$) and left circularly polarized ($\phi=3\pi/2$).

In HELIOS-I the two field components have equal strength at all gaps, but as can be seen from Table 2 this is much less than that of a conventional vertical field (Halbach configuration) undulator. HELIOS-II gives higher field strengths, but the they are no longer equal. In the version finally adopted at the ESRF (HELIOS-III) the lower array is replaced by a conventional vertical field structure which further increases the B_y component.

Owing to lack of symmetry this device also has a linear variation of both field components in the y-direction, of the same magnitude as for the adjustable phase ID, producing the same sensitivity to the vertical beam size and position. A further potential problem is the fact that the fields give rise to a second-order deflection of the trajectory [32]; a horizontal deflection in the case when $\phi \neq 0$, and vertical deflection when $B_{xo} \neq B_{yo}$. Since these effects are of second-order, and therefore inversely proportional to the Energy^2, the effects may become problematic in low energy rings. In the ESRF the horizontal deflection is overcome using two separate undulators with opposite helicity so that the two deflections cancel [33]. The two undulators are used in a "chicane" arrangement to produce radiation with opposite helicity displaced slightly to the left and right of the beam axis. The HELIOS device was installed in the ESRF in June 1993; no effect on beam lifetime was observed, and only small changes in closed orbit were produced, in agreement with expectations. Two further single section structures are under construction.

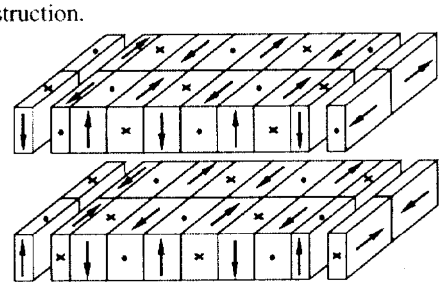

Figure 3. Planar helical undulator (PHU)

A modification of the HELIOS device is the planar helical undulator [32], shown in fig. 3. In this case both arrays produce a pure helical field, with equal field amplitudes that exceed that of the HELIOS device in the helical mode. A further advantage of this structure is that the symmetrical arrangement eliminates any second-order deflections. A significant disadvantage however is that the helicity is fixed.

Most recently a further device has been developed called APPLE (Advanced Planar Polarized Light Emitter), shown in fig. 4. The first structure to be put forward (APPLE-I) employed magnet blocks with a 45° magnetization [34]. Subsequently the simpler structure (APPLE-II) was developed in which each of the 4 arrays has a Halbach structure [35]. In both versions the upper-back and lower-front arrays produce a linearly polarized field given by :

$$B_x = B_{xo} \cos(kz)$$
$$B_y = B_{yo} \cos(kz)$$

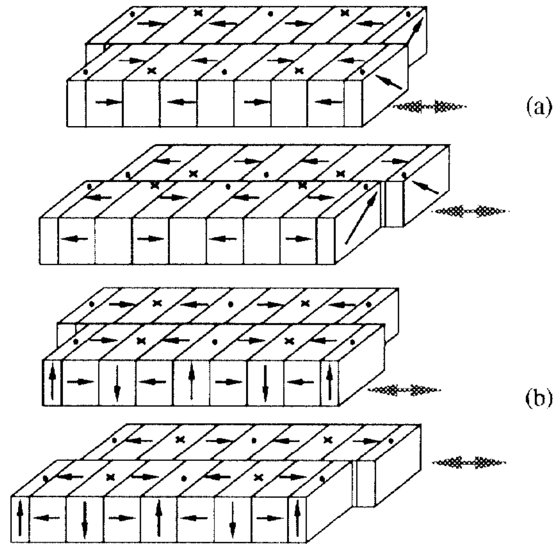

Figure 4. Planar helical devices, (a)APPLE-I, (b) APPLE-II

The upper-front and lower-back arrays are shifted with a variable phase ϕ with respect to the other two arrays, and generate a field given by :

$$B_x = -B_{xo} \cos(kz + \phi)$$
$$B_y = B_{yo} \cos(kz + \phi)$$

Adding the two together and simplifying results in the following :

$$B_x = 2B_{xo} \cos(kz + \phi/2 + \pi/2)\ \sin(\phi/2)$$
$$B_y = 2B_{yo} \cos(kz + \phi/2)\ \cos(\phi/2)$$

Unlike the HELIOS case, the field amplitudes and hence output wavelength do depend on ϕ. Thus a value of phase exists for any gap that will give equal field amplitudes i.e. the helical mode. An interesting property of this device is that the two field components remain 90° out of phase, and hence the polarization ellipse remains upright. The Stokes' parameters (in the low K limit) are given by :

$$S_1 \sim B_{yo}^2 \cos^2 \phi/2 - B_{xo}^2 \sin^2 \phi/2 \qquad S_2 \sim 0 \qquad S_3 \sim B_{xo} B_{yo} \sin \phi$$

Table 2 shows that the field of the APPLE-I device is significantly higher than any of the earlier structures. It is interesting to note that the maximum vertical field amplitude exceeds that of a conventional device by up to 16 % at the longest period length, due to the 45° magnetization angle. Such a method could therefore be employed even for a linear device to obtain the highest possible field strength, but at the expense of transverse field homogeneity. The APPLE-II device, as well as being easier to construct, produces a larger B_x field at the expense of smaller B_y (maximum value equal to that of a conventional ID) and hence also higher field in the helical mode.

The APPLE configurations have a greater degree of symmetry than the HELIOS ones, which eliminates problems due to second-order steering effects. The transverse field homogeneity however remains considerably worse than in a conventional device. A full beam dynamics simulation of the effects of such devices has yet to be carried out, however recent tests at JAERI and SSRL have given very encouraging results.

Table 2
Peak field amplitudes (T) in horizontally (B_x), vertically (B_y) and helically ($B_{x,y}$) polarized modes for various planar magnetic structures : (1) Halbach, (2) Helios-I, (3) Helios-II, (4) Helios-III, (5) PHU, (6) APPLE-I, (7) APPLE-II. Block height = $\lambda_o/2$, width = 70 mm, B_r = 1.1 T.

Type :	(1)	(2)	(3)	(4)	(5)	(6)	(7)
λ_o = 40 mm							
B_x	-	0.083	0.108	0.108	-	0.180	0.216
B_y	0.393	0.083	0.157	0.196	-	0.419	0.393
$B_{x,y}$	-	0.083	0.108	0.108	0.120	0.165	0.189
λ_o = 60 mm							
B_x	-	0.162	0.206	0.206	-	0.331	0.411
B_y	0.656	0.162	0.276	0.328	-	0.725	0.656
$B_{x,y}$	-	0.162	0.206	0.206	0.241	0.302	0.349
λ_o = 80 mm							
B_x	-	0.226	0.281	0.281	-	0.434	0.562
B_y	0.834	0.226	0.363	0.417	-	0.947	0.834
$B_{x,y}$	-	0.226	0.281	0.281	0.348	0.398	0.469
λ_o = 100 mm							
B_x	-	0.275	0.335	0.335	-	0.495	0.670
B_y	0.951	0.275	0.423	0.475	-	1.101	0.951
$B_{x,y}$	-	0.275	0.335	0.335	0.436	0.458	0.556

A 7 period prototype of the APPLE-1 device was tested recently in the JAERI Storage Ring (JSR) [36]. Visible light was generated with variable polarization with a ring energy of 138 MeV. No beam deflections were observed while changing the gap or the phase.

An APPLE-2 device has recently been constructed for the SPEAR storage ring with 27 periods of 65 mm [37]. At minimum gap (30 mm) in the helical mode it produces a maximum field of 2 kG, which allows the device to operate over the 500-1000 eV photon energy range. This device includes a further modification, namely the ability to change the field strengths by phase rather than gap variation. This is achieved by shifting the relative positions of the two upper arrays with respect to the two lower ones, or the two front arrays with respect to the two back arrays. In this way no gap adjustment is required to set any desired output wavelength and ellipticity. The device has recently been tested in SPEAR with no noticeable effect on the 3 GeV beam.

4. SHORT-PERIOD DEVICES AND MICRO-UNDULATORS

Although the advantages of short-period undulators have long been recognised, the application to synchrotron radiation sources has been slow to develop, due to the difficulties associated with the small vertical gaps that are required.

Table 3 summarises the main parameters of various devices that have been built, or are under construction. The first three devices were designed for storage ring operation and all employ variable gap vacuum vessels, so as not to limit the aperture during injection and energy ramping. In each case the smallest possible vacuum chamber thickness is used, as small as 0.3 mm at the position of the poles in the MAX device, leading to minimum operational gaps only 1.5-2 mm larger than the internal aperture. The lifetime of the MAX beam at 550 MeV with a 6.2 mm internal gap is 1.7 hours. Since the beam loss process is predominantly elastic Coulomb scattering, the lifetime would be much better in higher energy rings, or alternatively even smaller gaps should be possible.

The prototype small-gap undulator (PSGU) for the NSLS X-ray ring employs a novel 6 magnet per period arrangement, rather than the usual 4, in order to gain a 6 % higher field. The design also incorporates a non-steering termination. In initial studies the vacuum chamber was closed to a gap of 3.35 mm with no observable effect on beam lifetime. Installation of the undulator is scheduled for June '94.

The second part of the Table lists other devices that have been built, the majority as part of development programmes for free-electron lasers. In this case since the electron beam passes only once through the device a small gap is less of a restriction. Many different types of pulsed device have also been developed, but will not be considered here.

Table 3
Parameters of various short period devices; units = mm, † = under construction/test.

λ_o	N	g_{min}	K	Type	Project
26.0	30	7.0	2.0	PPM	ESRF†
24.0	35	7.7	1.9	HYB	MAX [38]
16.0	19	6.0	0.9	PPM	NSLS [39]
21.8	220	4.8	1.9	HYB	[40]
18.0	26	8.6	0.9	SC	NSLS† [41]
15.0	40	5.0	1.0	HYB	UCLA [42]
10.0	5	5.0	0.33	HYB	[43]
8.8	23	4.4	0.4	SC	NSLS [44]
8.0	62	6.0	0.15	HYB	CREOL [45]
4.1	13	2.0	0.03	PPM	UCSB [46]

For the majority of the short period devices a hybrid construction has been chosen, which has allowed period lengths as short as 8 mm to be obtained, using conventional methods of assembling individual pole and magnet units. An alternative method for obtaining even shorter period lengths is a non-segmented approach [46,47]. The last device in the table was constructed in this way. Much smaller period "micro-undulators" can also be produced, as demonstrated by a device with a 0.726 mm period that reached a field amplitude of 0.3 T (K=0.02) with a 0.23 mm gap [48]. A summary of construction methods and applications is given in Ref. [49].

Superconducting technology has also been applied to construction of short period devices, and has been developed particularly at the NSLS for a FEL application. After successfully testing a prototype with 8.8 mm period, an 18 mm period device has been built and is currently under test.

5. LONG-PERIOD DEVICES

The prospect of long (≥ 20 m) straight sections becoming available in rings originally designed for High Energy Physics has led to the development of various concepts for devices that have long period lengths and low field strength but which have greater flexibility than conventional devices [50]. The flexibility to vary period length, total length, polarization, and introduce arbitrary tapering or field profiling has led to such devices being called "field synthesizers" (FS) [51]. Both linear and helical structures with either electric [52] or magnetic fields [53] have been proposed. There is an ongoing program of FS development at SSRL, but due to the high cost of such a device, with many independent channels, most of the work so far has been theoretical.

6. DYNAMIC FIELD UNDULATORS

Various possibilities exist for using dynamic electromagnetic or electric fields. Progress has already been made for example in using microwave radiation. A device operating at 2856 MHz giving an equivalent undulator period of 5.5 cm and field of 480 Gauss was tested successfully at the Photon Factory linac [54]. This device operated in a pulsed mode because of the high power requirements (300 kW for a 1 m structure). A superconducting cavity however can provide a sufficiently high shunt impedance to allow c.w. operation. A test cavity has produced fields of 300 Gauss with an equivalent period length of 2.5 cm in a 215 mm long device with 10 W of input power at 6 GHz [55]. More recently a 30-60 GHz device is being studied for the APS [56], while construction of a 120 GHz, 1.45 mm period, device is being considered for a compact mm-wave source [57]. Other developments could include very long undulators, a circularly polarized device or a hybrid permanent magnet and microwave device allowing the possibility to switch the helicity at several hundred Hz [58].

A natural extension to reach shorter wavelengths is the use of a laser. With a laser wavelength λ_L the equivalent undulator period is $\lambda_L/2$. The emission of undulator radiation is equivalent to Compton backscattering, which has already been used to produce gamma radiation of a few 100 MeV with high energy electron beams. With a lower energy beam of only 100 MeV, 1 Å radiation could be produced using a 10 µm CO_2 laser. The possibility of a constructing a soft X-ray free-electron laser using a laser undulator with an electron energy of less than 10 MeV has also been considered [59]. One of the main problems however is that very high laser intensities are required, ~ GW/mm^2, which is only possible with short ns pulses with low repetition rate.

Another possibility is the use of purely electric fields in the form of plasma waves [60], generated by either wake field or laser beat wave excitation, both of which are being studied as mechanisms for high gradient acceleration. With plasma densities currently available undulators with an equivalent wavelength of 100 µm and field of 100 T could be produced. The source must be pulsed, and since the electron beam must traverse the plasma a single-pass operation is more suitable than a storage ring.

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