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OPHÉLIE: a variable-polarization electromagnetic undulator optimized for a VUV beamline at Super-ACO

L. Nahon,[a,b]* M. Corlier,[a] P. Peaupardin,[a] F. Marteau,[a] O. Marcouillé[a] and C. Alcaraz[a]

[a]LURE, Bâtiment 209D, Université Paris-Sud, 91405 Orsay CEDEX, France, and [b]CEA/DRECAM/SPAM, Bâtiment 522, CE Saclay, 91191 Gif-sur-Yvette CEDEX, France. E-mail: nahon@lure.u-psud.fr

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A planar/helical crossed overlapped undulator, called OPHÉLIE, is presented, composed of two identical ten-period (each 25 cm long) crossed undulators whose magnetic fields are produced by electromagnets. Such a design is quite simple, with only one mechanical translational motion, and versatile. After the presentation of the general concept of the crossed undulator and of its actual magnetic design, the expected performances in terms of flux and polarization capabilities are described. It appears that any state of polarization can be produced, at least on the first harmonic, with a large total polarization rate and a potentially high polarization switching frequency.

Keywords: insertion devices; electromagnets; crossed undulators; polarization.

1. Introduction

A new undulator-based low-energy/high-resolution beamline, called SU5, is under construction on the 800 MeV Super-ACO storage ring. The undulator should feed, with a high photon flux, a 6.65 m normal-incidence monochromator whose target resolving power is higher than 10^5 in the 5–45 eV VUV photon-energy range. The primary scientific goal of the SU5 beamline mostly deals with photon-induced dynamics, electronic structure studies and high-resolution spectroscopy of very dilute samples such as clusters, radicals and excited species.

Apart from this 'conventional' scientific goal, a second scientific goal consists of the use of 'exotic polarizations' such as rotatable linear and circular polarization, allowing the study of linear and circular dichroism on anisotropic and/or oriented species such as fixed-in-space molecules, laser-aligned atoms, adsorbed molecules on surfaces and magnetic materials. In order to obtain high flux and polarization rates, numerous schemes of insertion devices have been proposed, including asymmetric wigglers, helical/elliptical undulators and crossed undulators (for a review see Elleaume, 1989; Kim, 1990; Walker & Diviacco, 1992; Walker *et al.*, 1997).

For the sake of versatility we chose to adopt the crossed overlapped undulator scheme in which two orthogonal identical planar undulators generate separately a vertical and a horizontal magnetic field, and where the longitudinal phase between the two undulators sets the polarization type as proposed by Onuki (1986). A four-period prototype of such a device with permanent magnets has been tested and successfully used on TERAS (Onuki *et al.*, 1989; Yagi *et al.*, 1992, 1995) in the visible and VUV ranges. More recently, a 15-period (each 8.6 cm long) Onuki-type undulator has shown very promising results in the near-UV range on NIJI-II (Yuri *et al.*, 1996).

We wish to present here a large-scale ten-period Onuki-type crossed undulator, based, for the first time, on electromagnets, so that the only mechanical motion is the longitudinal displacement, and polarization flipping is actuated by a simple inversion of the polarity of one of the power supplies driving the magnetic fields. Such a device, optimized for the VUV range, should be able to produce any kind of polarization, either fixed linear for 'conventional' spectroscopy or 'exotic' for dichroism experiments. It will be seen also as a large-scale prototype for future third-generation storage-rings insertion devices. In the following we will use the name OPHÉLIE (Onduleur Plan/Hélicoidal du Lure à Induction Electromagnétique) to refer to the Super-ACO Onuki-type crossed overlapped undulator.

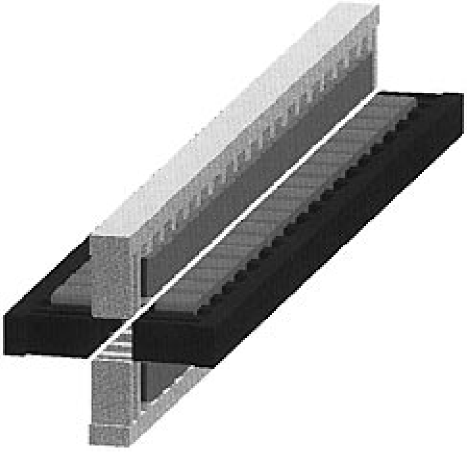

Figure 1
Scheme of the 2.5 m long fixed-gap electromagnetic crossed undulator, composed of two crossed undulators with ten periods of 25 cm. The only mechanical motion is a longitudinal translation of the vertical undulator (the end correction poles but not the corresponding coils have been drawn).

2. General concept and actual design

OPHÉLIE, as displayed in Fig. 1, is constituted of two identical and perpendicular planar undulators, defining a vertical (with peak value B_{0y}) and a horizontal (with peak value B_{0x}) sinusoidal magnetic field. A mechanical translation of the vertical undulator allows a relative dephasing between the two undulators. With such a device the transverse idealized magnetic field can be written as

$$B_t = \hat{u}_x B_{0x} \cos(2\pi z/\lambda_0) + \hat{u}_y B_{0y} \cos(2\pi z/\lambda_0 - \varphi), \qquad (1)$$

where z is the longitudinal coordinate and φ is the relative translational dephasing between the two undulators.

The photon energy of the nth harmonic observed on-axis does not depend on φ but only on the strength of the total peak magnetic field *via*

$$\begin{aligned} \varepsilon_n[\text{eV}] &= 950E^2[\text{GeV}]/\{\lambda_0[\text{cm}](1 + K_x^2/2 + K_y^2/2)\} \\ &= 12\,400/\lambda_n[\text{A}], \end{aligned} \qquad (2)$$

where K_x and K_y, the horizontal and vertical deflection parameters, are given by

Table 1
Electromagnetic and geometrical parameters of the two identical planar undulators constituting OPHÉLIE.

Type	Electromagnetic
Number of periods	10
Period length	250 mm
Maximum peak field on-axis	0.11 T ($K_{\max}$ = 2.57)
Magnetic gap	110 mm
Pole material	Laminated steel (1 mm thick sheets)
Number of poles	22 per undulator
Maximum current, $I_{\max}$	210 A ($NI_{\max}$ = 8400 ampere-turns)
Power supplies	Horizontal: 210 A, 135 V Vertical: ±210 A, ±190 V

$$\begin{aligned} K_x &= 0.934 B_{0x}[\mathrm{T}]\lambda_0[\mathrm{cm}], \\ K_y &= 0.934 B_{0y}[\mathrm{T}]\lambda_0[\mathrm{cm}]. \end{aligned} \tag{3}$$

The polarization of the light emitted by such a planar/helical insertion device depends on the trajectory of the electrons.

Several cases can be considered:

(i) $\varphi = 0$. The total magnetic field is sinusoidal, with a linear pattern in the xy transverse plane. For symmetry considerations, the light is linearly polarized in a plane making an angle α with the horizontal plane, where $\tan\alpha = B_{0x}/B_{0y}$. Any value of the angle α can be achieved leading to a rotatable linear polarization. For instance, linear vertical polarization, the standard mode of operation of the beamline, will be obtained by setting $B_{0y} = 0$.

(ii) $\varphi = \pm\pi/2$ and $B_{0x} = B_{0y}$. The total magnetic field is helical with a circular pattern in the xy transverse plane. The light emitted is then circularly polarized with a helicity depending on the sign of φ (or B_{0y}).

(iii) None of the above configurations. The polarization is then elliptical with any desired required characteristics since, as it will be shown later, there is a one-to-one relationship between the three Stockes parameters of the emitted light and the three continuously tunable undulator parameters, B_{0x}, B_{0y} and φ. Although the only interesting polarizations at the sample level are the purely linear and circular cases, it is important to be able to generate any elliptical polarization since a given polarization state will be modified by the different reflections on the optics, which have different complex reflectivities for the s and p components.

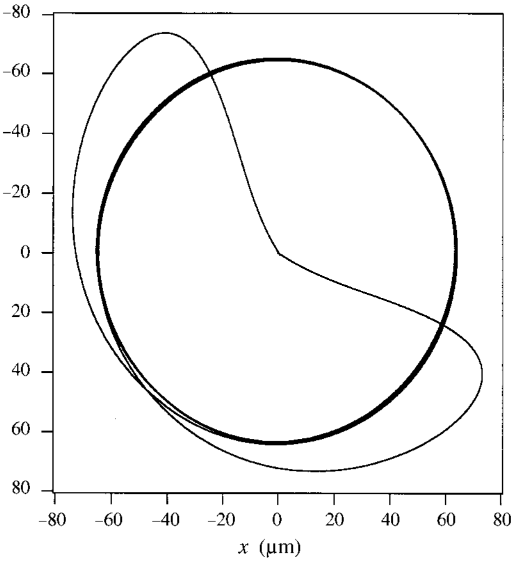

Figure 2
Electron trajectories, viewed in the transverse xy plane, corresponding to the left- and right-handed circular polarizations: $B_{0x} = B_{0y} = B_{\max} = 0.11$ T and $\varphi = \pm\pi/2$. The curves are superimposed and described in opposite directions.

As compared with the permanent-magnet Onuki undulator (Onuki, 1986) or with other permanent-magnet-based helical/elliptical insertion devices (Elleaume, 1990; Sasaki, 1993), the use of electromagnets makes OPHÉLIE quite simple in principle and very versatile, with the only longitudinal motion limited to $\pm\lambda_0/4$ ($\pm$6.25 cm). With such a translation range, the use of a bipolar power supply driving the vertical magnetic field allows one to reach any actual dephasing value. In addition, and this is of course a major point, the use of electromagnets allows, in principle, a relatively high polarization flipping speed, certainly up to a few tens of Hertz, by flipping the polarity of the vertical magnetic field, as long as the power supplies and the magnetic time constants of the system follow. Unfortunately, in the specific SU5 case, because of an odd 2° vertical elevation angle of the beamline, the polarization flipping will generally require, in addition, a small change in the mechanical longitudinal translation setting, so that the flipping frequency will be of the order of 1 Hz.

As has been extensively discussed elsewhere (Nahon *et al.*, 1997), we chose to use long periods (25 cm) and a weak peak magnetic field (0.11 T) in order to limit the thermal load on the first optics to a few Watts. This is especially necessary in our case of normal-incidence-mounted optics which would strongly absorb any high-energy photon (above 50 eV). Note that this magnetic structure appears to be very suitable for the electromagnetic technology.

One of the difficulties encountered with OPHÉLIE is the presence of a horizontal undulator to generate the horizontal magnetic field, which is not the case, for instance, for planar arrays generating helical/elliptical fields such as HELIOS (Elleaume, 1990) or APPLE (Sasaki, 1993), which are only concerned with the vertical transverse dimension of the ring vacuum vessel. Since OPHÉLIE's geometrical structure is totally symmetric with respect to the horizontal and vertical planes, we decided to adopt a circular vacuum chamber, leading to (for beam stay-clear consideration) a minimum possible magnetic gap of 90 mm for both undulators.

In order to avoid a reduction of the stored beam lifetime, the magnetic fields have to be as uniform as possible around the central axis. This imposes some severe constraints on the geometry of the poles. Indeed, the larger the poles in the x (y) transverse dimension for the vertical (horizontal) undulator, the more uniform are the fields. Of course, because of OPHÉLIE's crossed structure, as one increases the pole width one has to increase the gap of both undulators. There is thus a trade-off to be found between the fulfilment of roll-off conditions and the required ampere-turns necessary to achieve the desired maximum magnetic field strength. The optimized geometry consists of a transverse pole width of 100 mm and a 110 mm fixed gap for both undulators. Since a maximum magnetic field on-axis of 0.11 T is required, the electromagnetic and geometrical parameters of the poles and coils as listed in Table 1 have been chosen.

In order to limit any closed-orbit displacements and non-linear effects, tolerances on the regular and skew multipole field components led to severe constraints on the mechanical accuracy of the poles machining (Nahon *et al.*, 1997). Provided they are respected, which should be quite easy considering the low value of the peak magnetic field, the beamline users will have total control over the three parameters of OPHÉLIE, B_x, B_y and φ, independently of the control room.

In order to have the trajectory of the electrons as centred on the axis as possible for any setting of OPHÉLIE, special attention has to be paid to the end correction coils. A specific geometry of a double set of coils has been designed, concerning poles 1 and 22 (outer-end correction coils) and poles 2 and 21 (inner-end correction coils), to be implemented on both extremities of the four jaws. This double correction coils geometry is very efficient, as can be seen in Fig. 2, showing that the circular polarization flipping will not affect the positron trajectories, and thus the photon beam, which remains centred around the z axis within a few micrometres.

3. Expected polarization capabilities

Fully polarized light can be decomposed into three components on the Poincaré sphere, S_1, S_2 and S_3, called the Stockes parameters, such that if S_0 stands for the total flux, one has

$$S_0^2 = S_1^2 + S_2^2 + S_3^2. \tag{4}$$

With the standard definition, S_1 is the linear 'normal' polarization parameter, S_2 is the linear 'tilted' polarization parameter and S_3 is the circular polarization parameter. To these S_i (i = 1–3) parameters are related the partial polarization rates P_i (i = 1–3) such that $P_i = S_i/S_0$. In the case of OPHÉLIE, these three partial polarization rates are linked to the three parameters K_x, K_y and φ *via* (Elleaume, 1994; Nahon *et al.*, 1997)

$$\begin{aligned} P_1 = S_1/S_0 &= (A^2 - B^2 - C^2)/(A^2 + B^2 + C^2) \\ &= (K_y^2 - K_x^2)/(K_x^2 + K_y^2) = (\rho^2 - 1)/(1 + \rho^2), \end{aligned} \tag{5}$$

$$\begin{aligned} P_2 = S_2/S_0 &= 2AB/(A^2 + B^2 + C^2) \\ &= -2K_xK_y \cos\varphi/(K_x^2 + K_y^2) = -2\rho\cos\varphi/(1 + \rho^2), \end{aligned} \tag{6}$$

$$\begin{aligned} P_3 = S_3/S_0 &= 2AC/(A^2 + B^2 + C^2) \\ &= -2K_xK_y \sin\varphi/(K_x^2 + K_y^2) = -2\rho\sin\varphi/(1 + \rho^2), \end{aligned} \tag{7}$$

where ρ is the magnetic strength ratio given by $\rho = K_y/K_x$. Note that the expressions of P_i as a function of K_x, K_y and φ are exactly the same (except for some signs) as defined directly from the amplitudes a_1 and a_2 and the relative phase δ of a plane wave with electric field components $E_x = a_1 \exp[-i(\omega t - kz)]$ and $E_y = a_2 \exp[-i(\omega t - kz)] \exp(-i\delta)$.

Several straightforward comments can be made: (i) by setting the proper OPHÉLIE parameters, any polarization state of the light can be produced at any photon energy for $n = 1$; (ii) the three partial polarization rates are independent of the harmonic number n, and P_1 is, in addition, independent of φ; (iii) since P_1, P_2 and P_3 are linked by (4), these three partial polarization rates depend only on two independent parameters, ρ and φ, and are then independent of the emitted photon energy.

It is useful to reach the general case of elliptical polarization in two main cases.

(*a*) When, because of the dephasing on the optics, a given set of (P_1, P_2, P_3) has to be reachable for each photon energy. In this case the photon energy imposes $K_x^2 + K_y^2$, P_1 imposes ρ and P_2 [linked to P_3 *via* (4)] gives φ.

(*b*) If a large degree of circular polarization is needed in the high-energy part of the spectrum, *e.g.* above 20 eV, so that high harmonics emission is required. As for other exotic insertion devices, there is then a trade-off between the flux and the circular polarization rate P_3. Considering that the figure of merit in dichroism experiments generally scales as $P_3^2F_n$ ($n > 1$), one can set, for example, $\rho = 0.5$ and $\varphi = 75°$, or $\rho = 1$ and $\varphi = 45°$.

Up to now we have only considered the ideal case of a filament beam passing through a perfect insertion device and observed at infinity on-axis, so that the light was fully polarized and equation (4) strictly holds. Of course, in reality there are several causes of depolarization, such as non-zero emittance effects, the angular integration by the beamline and magnetic inhomogeneities (mostly transverse fields gradients) of OPHÉLIE. All these effects lead to a total polarization rate smaller than unity, because part of the light is unpolarized.

The transverse gradients of magnetic fields have already been minimized so that their effect should be quite small. The angular integration effect has been studied by simulations which show that whatever is the magnetic configuration of OPHÉLIE, the unpolarized light fraction remains below 0.5% as long as the angle of integration does not exceed twice the central cone total aperture. We are confident that the emittance depolarization effects should remain of the same order of magnitude, typically below a few percent.

4. Conclusions

Two long-period weak-magnetic-field undulators are used for the construction of a crossed overlapped undulator based on electromagnets. Such a concept allows us to reach, in the VUV range, high polarization rates with flexibility. Generally speaking, the OPHÉLIE concept is certainly able to switch frequency in the 10–100 Hz range, although in the specific SU5 case, because of the beamline implementation constraints, it is not worth operating it faster than 1 Hz. OPHÉLIE is presently under construction, and should pass a severe series of magnetic calibration and testing, including the use of a three-dimensional Hall probe, rotating-coil and pulsed-wire techniques, during the autumn of 1997, in order to be installed on the ring in early 1998. Several months are then scheduled to perform, with the beam, a complete calibration and characterization of this insertion device and especially of its polarization capabilities, with a four-reflection phase shifter and analyzer.

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