LURE

MENESR

Département Anneaux

Super-ACO/99-12
Rubrique : Rapport de Synthèse

PERFORMANCES OF OPHéLIE :
A NEW TYPE OF UNDULATOR AT LURE

J.-C. BESSON, P. BRUNELLE, J. CLAVERIE, M. CORLIER, J.-M. GODEFROY, C. HERBEAUX, D. LEFEBVRE, O. MARCOUILLE, J.-L. MARLATS, F. MARTEAU, J.-P. MARX, L. NAHON, P. PEAUPARDIN, A. PETIT, M. SOMMER, J. VETERAN.

Presented at the 16th International Conference on Magnet Technology

September 26 – October 2, 1999

Ponte Vedra Beach, Florida, USA

September 1999

Laboratoire pour l'Utilisation du Rayonnement Électromagnétique

Bâtiment 209D - Centre Universitaire Paris-Sud – BP 34 - 91898 ORSAY Cedex
Tél. (1) 64.46.80.00 - Télefax (1) 64.46.41.48

INTERNET : LUREMAIL@LURE.U-PSUD.FR

Performances of OPHELIE : a new type of undulator at LURE*

M. Corlier, J.-C. Besson, P. Brunelle, J. Claverie, J.-M. Godefroy, C. Herbeaux, D. Lefebvre, O. Marcouillé, J.-L. Marlats, J-P. Marx, F. Marteau, P. Peaupardin, A. Petit, M. Sommer, J. Vétéran (1), and L. Nahon (1)(2).

(1) LURE, Université Paris-Sud, Bât. 209 D, BP 34, 91898 Orsay cedex France
(2) CEA/DRECAM/SPAM, Bât. 522, CE Saclay, 91191 Gif sur Yvette France

Abstract--**The first electromagnetic Onuki-type undulator has been operating on the 800 MeV storage ring Super-ACO since spring of 1998. It consists of two crossed overlapped, 2.7 meter long, undulators able to produce any kind of polarized light in the VUV energy range with a switching rate of 1 Hz. The maximum magnetic field of 0.12 T is produced in both planes by the mean of bipolar ± 210 A/± 190 V and monopolar 210 A/135 V power supplies. The undulator producing vertical magnetic field can be shifted along longitudinal axis in order to change the phase of magnetic fields. Main design is summarized: mechanical structure, different sets of correcting coils, water cooling. Magnetic measurement results obtained by different methods are described, in particular, the tuning of the beam transverse excursion according to the main current variations and the flux capture effect when the phase is changing. A good agreement was found between magnetic measurements, calculations and on-beam tests.**

I. INTRODUCTION

We have already presented at the latest conference [1] the main design of this new type of undulator (Fig.1) called OPHELIE (Onduleur Plan/Hélicoïdal du LURE à Induction Electromagnétique) installed on Super-ACO [2]. We have used a fully electromagnetic technology to produce both the horizontal (B_X) and vertical (B_Y) magnetic fields which can be tuned by simply varying the current from the main power supplies.

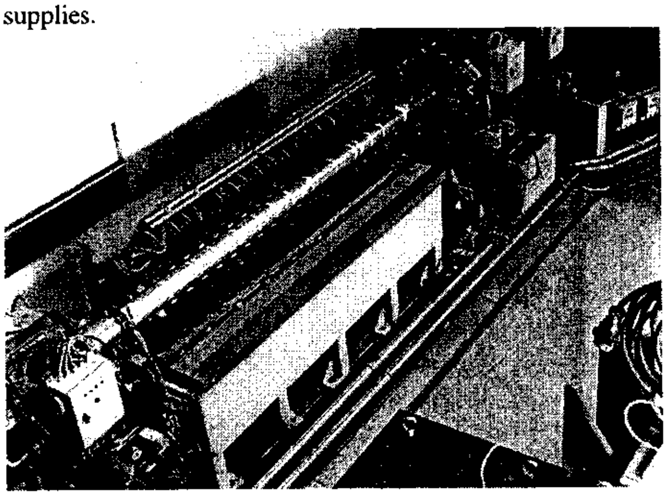

Fig. 1. View of one part of OPHELIE in Super-ACO

The main interest of this technology resides in its potential high switching speed of the photon helicity by flipping the polarity of the vertical field with a bipolar power supply.

*Work supported by CNRS, CEA, MENRT and submitted on September 27, 1999.

By convention the vertical (resp. horizontal) undulator, called V-undulator (resp. H-undulator) is the one producing a sinusoidal magnetic field in the vertical (resp. horizontal) plane. A translational motion of the V-undulator (over half a period) allows the tuning of the phase ϕ between B_y and B_x. In order to fully understand the behavior of the undulator in itself, its effects on the beam, and the produced spectrum, we have fully commissioned, during the year 1998, the OPHELIE Insertion Device (ID) in the DC mode of operation. The main parameters of the device are summarized on Table 1.

TABLE 1

Type	Crossed, overlapped and fully electromagnetic
Number of effective periods	9 in both planes
Period length (mm)	250 in both planes
Maximum measured peak field on axis (T)	B_{ox} = 0.126, B_{oy} = ± 0.126 at 210 A ($K_{xmax} = K_{ymax}$ = 2.94)
Gap (mm)	110 in both planes
Pole material	Laminated steel (1 mm-thick sheets)
Number of poles	18 main poles + 4 correction poles
Pole length in z direction (mm) for both undulators	46 (poles # 3 to 20) ; 38 (poles # 2 and 21) 16 (poles # 1 and 22) after machining
Pole width in x, y direction (mm)	100
Return yoke width (mm)	50 (solid steel)
Overall length (mm)	2 686 (including ± 72 mm translation)
Maximum current I_{max} (A)	210 (NI_{max} = 8 400 A.turn per main coil for both undulators)
Switching frequency	DC to 1 Hz

II. CONSTITUTING ELEMENTS

A. Magnetic design and poles manufacturing

As the undulator is devoted to produce any kind of switchable polarization, electromagnetic technology was chosen. This choice takes into account different constraints. First, the period length, 25 cm, resulting from the optimization for the VUV range [3], was large enough to allow the installation of coils around the poles. This was more adapted and effective than using large blocks of permanent magnets which would have not been sufficiently magnetically homogeneous. Second, as the device operates on a storage ring, the hexapolar component (H) of the peak field variation has to be limited to 30 $T.m^{-2}$ ie $(\Delta B/B)_{max}$ = 2.5 % at 10 mm. This had led to optimize the pole width. Each undulator is made of 22 poles. There are nine full effective periods in each undulator. The 18 central poles named "main poles" are equipped with main coils, which produce the main field, and with compensation coils, designed to compensate for local peak field variations along the undulator. One set of correction coils are wound on poles # 1 and # 22 and are connected in series driven by a i1 current. Similarly the set of correction coils wound on poles # 2 and # 21 are connected in series and driven by a i2 current (Fig. 2). These correction coils have to tune the angle and the average position of the positron trajectory inside the undulator. One should mention that pole # 2 at the entrance and its symmetrical pole # 21 at the exit are also equipped with other water cooled coils which are electrically connected in series with the main coils in order to complete the effect of correction coils. One can specify that correction and compensation coils are made of flat enameled wire whereas the 18 main coils and the additional ones on poles # 2 and # 21 are made of square copper with a water cooling circuit. 3D simulations were very helpful to finalize the design and the whole geometry, in particular to check the Ampere-turn consumption with the required peak-field value of 0.12 T, to check the saturation level of main poles and to validate the 2D evaluation of the transverse peak field variation ($\Delta B/B$). The adequate pole width was evaluated with the 2D code [4] and confirmed with the 3D code [4] in order to keep $H \leq 30\ T.\ m^{-2}$.

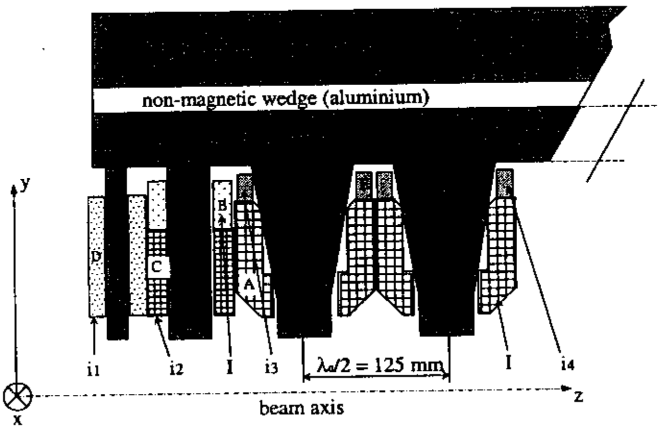

Fig. 2. Mechanical cross section of end poles.

This optimization was obtained as a compromise between the transverse width of the poles and the required Ampere.turns. A 110 mm gap was finally chosen with a 100 mm pole width. In addition, a shortened model of three periods was modelized to control the field helicity for different phases. All the above simulations were made with a static field, but as the device is designed for switchable helicity (typically 1 Hz rate), we decided to use laminated steel for the poles in order to reduce eddy-currents that might limit the switching speed. So, the four jaws constituting the poles are laminated, the frame is made of 50-mm thick solid steel. The laminations were punched with a comb-shape (poles + yoke). The circulation of the flux lines in the pole and the yoke has led to stack the sheets in the vertical plane. An estimation of the "skin depth" was found to be 1.88 mm, for f = 1 Hz given by :

$$e(\text{cm}) = 5\,033\sqrt{\rho / \mu f}$$

with $\rho\ [\Omega/\text{cm}^3] \cong 9.8.10^{-6}$ for steel resistivity, $\mu \cong 7\,000$ (relative magnetic permeability). Finally, we chose poles made of 1 mm laminations in order to reach a maximum 5 Hz switching frequency which is expected for a future possible upgrade of OPHELIE. The quality of the chosen steel is silicon iron (V1 200-100 A from EBG Gesellsschaft-Bochum), without oriented grains and with a low coercitive field (Hc = 64 A/m.). The laminated sheets are coated with a 7 µm Stabolit layer in order to be glued after stacking.

B. Mechanical design and tolerance

OPHELIE is made of two crossed undulators : the H-undulator has two fixed jaws of electromagnets, while the V-undulator has two moveable jaws of electromagnets on a ball bearing carriage system, which is activated by a remote-controlled synchronous motor. The V-undulator is able to move from + 72 mm to - 72 mm in the z direction with respect to the H-undulator. (Note that ± 62.5 mm translation of the V-undulator corresponds to ± 90° in phase variations). The four jaws are mechanically coupled to a solid stainless steel frame, and electrically insulated by a caption foil and magnetically insulated by an aluminum wedge. The whole device can be split into two L-shaped parts in order to allow for the installation onto the ring (see Fig. 1). The vacuum chamber is maintained at its end flanges by two ion pumps fastened to the main support. The overall device weights about 6 tons. Special care was taken so that all the mechanical specifications and tolerances were tested during the manufacturing stage. 19 different control points were defined and checked before the delivery of the device at LURE. All tolerances had to be fulfilled with the main currents set to their maximum values and for any tuning of the phase ϕ. Typically, the transverse parallelism between jaws is better than 0.30 mrad (1 mrad required) while the longitudinal one is of 0.02 mrad (0.1 mrad required), the two undulator axis are aligned within 0.02 mrad (0.2 mrad required) and the measured gap is 109.85 ± 0.15 mm. Finally, the poles (H/H or V/V) are in front to each other within 0.1 mm (± 0.2 mm required) with a reproducibility of the H ± V positioning of ± 0.17 mm with the full current load.

C. Vacuum chamber

A new circular vacuum chamber was installed in the straight section # 5 of Super-ACO for the new undulator and was designed according to the following criteria :

- A 2.7 m long distance is preserved for the undulator including the V-undulator translation.
- As the 4 jaws of the undulator are close to the vacuum chamber, the two sputter ion pumps (120 $\ell.\ s^{-1}$) have to be located at the end flanges of the device.
- As the vacuum chamber is trapped inside the undulator, the bake-out jacket cannot be removed.

All the parts of the vacuum chamber are made of 316 L stainless steel. For magnetic reasons, the central part of the vessel is made of a non welded tempered tube. The two pumping tees at each end of the vessel have also be tempered to reduce the magnetic permeability of the welding. In order to stop the radiation emitted in the upstream dipole magnet, a photon absorber is located inside the first pumping tee at

25 mm from the beam axis. This absorber made of OFHC copper protects only the first half of the vacuum chamber from the radiation. A 10 W total power is deposited on the 1.3 m remaining length. Despite this rather low value of power, temperature increase might appear because of the thermal insulation of the bake-out jacket. This led us to install 4 water cooling circuits glued on the chamber with thermal cement. These cooling tubes are located at 45° from the vertical and horizontal axis in order to avoid contact with the poles. The bake-out is completed with 4 non magnetic heating resistances and a 5 mm thick insulating jacket made of ceramic powder. A 5 mm wide clearance is kept between insulation and magnet poles in order to avoid contact during the V-undulator translations. The vacuum chamber is baked at 180 °C. The temperature on the external face of the insulation is then 75 °C.

D. *Power supplies*

There are 3 families of power supplies in order to drive the 5 different types of coils (see figure 2). The minimum switching speed is limited to 2.5 seconds to flip from – 210 A to + 210 A, due to the coupling between the coils.

III. MAGNETIC MEASUREMENTS

Magnetic measurements have been performed using a Hall probe and the Pulsed Wire Method (PWM). Preliminary tests of current switching have been performed in order to evaluate the reproducibility of the magnetic field. At 80 A and 140 A the field reproducibility is 2.3 10^{-4} which is negligible in terms of closed orbit distortion and radiated wavelength shift. Additional measurements with the undulator off, show the remanent field low level : the magnetic field oscillates sinusoidally with amplitudes of only 2 10^{-4} T and a maximum residual integral of 3 10^{-5} Tm (compatible with the tolerances).

A. *The pulsed wire method measurements at $\phi = 0$*

The PWM, developed by R.W. Warren [5], has been used routinely during the whole measurement period to center the positron path (within 40 μm) on the undulator axis for $\phi = 0$. The main advantage of the PWM is the fast measurement of the magnetic field (within 30 seconds). The complete method and the results are presented at this conference [6]. The centering path tests have been performed for all main currents in both planes. But, preliminary measurements showed that the saturation level of poles # 2 and # 21 differs from the calculation. Beyond ± 100 A it was not possible to keep simultaneously the centre of the trajectories on axis and to cancel the average trajectory angle. Angle tolerances have been relaxed up to 50 μrad which is the acceptable limit for angular photon collection. The saturation effect appears clearly on the figure 3. It presents the variation of correction currents i1 and i2 (a linear variation law has been chosen for i2) which are required to center the trajectories. The double "S" curve shows how the saturation effects make i1 different from a linear law beyond ± 100 A and how hysteresis effects enlarge the curve. As the main current I varies, the correction current i1 must follow the hysteresis cycle in the way indicated on fig. 3 in order to reproduce the correcting magnetic field after several current switching. A similar behavior has been observed for the H-undulator : a "U" curve between 0 and 200 A (Fig. 4).

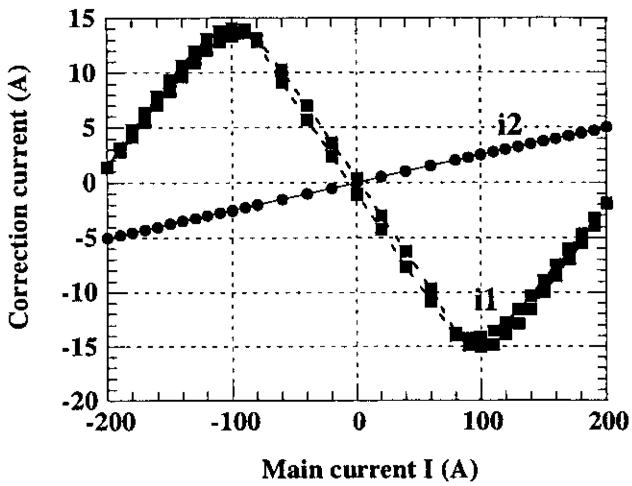

Fig. 3. Correction currents for V-undulator

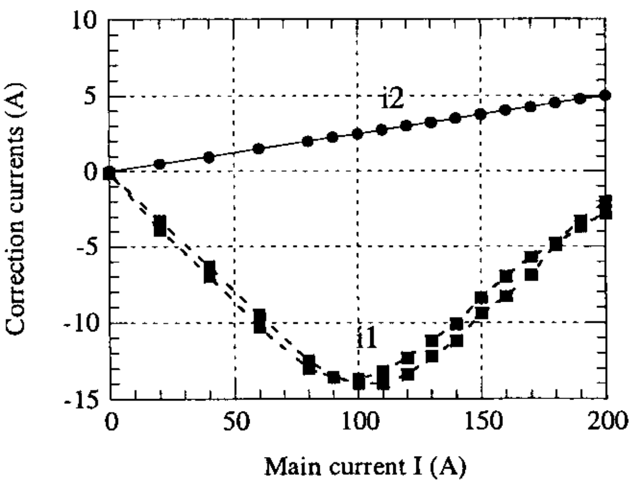

Fig. 4. Correction currents for H-undulator

Finally, the double curves are replaced by averaged curves, which actually do not change the closed orbit, and allow faster operation of the ID.

B. *Hall probe measurements at $\phi = 0$*

Figure 5 presents the B_x and B_y components measured by Hall probe. The current of the H-undulator (resp. V-undulator) is set to 200 A (resp. – 200 A). In addition, measurements as a function of the main current and the transverse position have been performed. The main results are summarized in the Table 2. Measurements and calculations are in very good agreement for the transverse homogeneity, the peak field and the linearity. In addition, the spectral broadening effect due to the peak field dispersion is very small (0.3 % to be compared to the natural spectral bandwidth of 10 %). Moreover, the natural focusing effect of the two undulators, measured on positron beam has confirmed homogeneity and peak field values predicted by magnetic measurements [7].

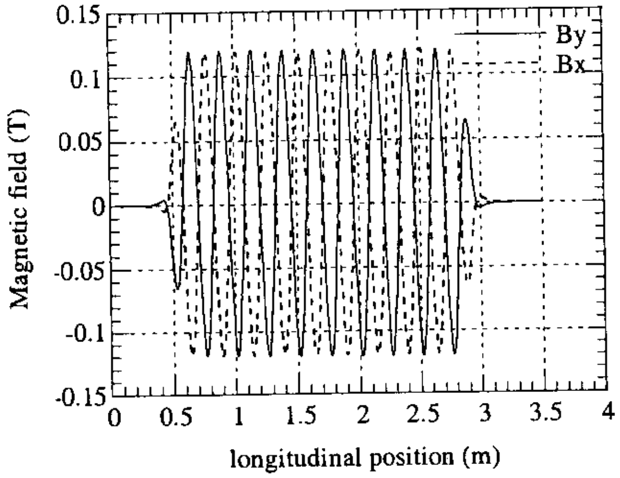

Fig. 5. Measured fields at ± 200 A with $\phi = 0$.

TABLE 2

	B_{omax}	$\sigma B_o/B_o$	$\Delta B/B_o = f(x)$	$B_o = f(I)$
Measurements	0.12 T @ 200 A	0.4 %	3 % @ ± 10 mm	5.99 10^{-4} T/A r = 0.999
Calculations	0.121 T @ 200 A	/	2.5 % @ ± 10mm	5.90 10^{-4} T/A r = 1

C. *Hall probe measurements at $\phi \neq 0$*

When the phase varies, the interaction of the vertical poles with the horizontal poles results in a reduction of the mutual flux capture. Indeed, at $\phi = 0$, transverse poles (vertical and horizontal ones) are spaced by only 11 mm. Then a maximum amount of the magnetic flux produced by the vertical poles is captured by the horizontal poles (and vice-versa) which reduces the peak field. When the phase between undulators varies from 0° to ± 90°, the mutual flux capture is reduced, resulting in the increase of line field density on the undulator axis : the magnetic peak field increases. Fig. 6 presents a zoom of one half-period of B_y when the ϕ varies from 0° to 90°. For each measurement, only one undulator is on. The relative increase of each component is typically 0.08 % per degree of phase. Similarly to the effect on B_x and B_y, when ϕ varies from 0° to ± 90°, the magnetic field produced by the end correction poles is increased (in absolute value). But the increase is not the same at the entrance and at the exit because the magnetic environment is not symmetric any more. The magnetic field integral is then over-corrected and thus produces kicks at the entrance or at the exit of each undulator. It has been noticed that the value of the kick generated by one undulator depends on the field intensity of this undulator only and on the absolute value of ϕ (third order polynom in ϕ). The location of the kick (entrance or exit), however, depends on the sign of ϕ : when $\phi > 0$, the magnetic default is mainly located at the entrance of the H-undulator and at the exit of the V-undulator and is reversed for $\phi < 0$.

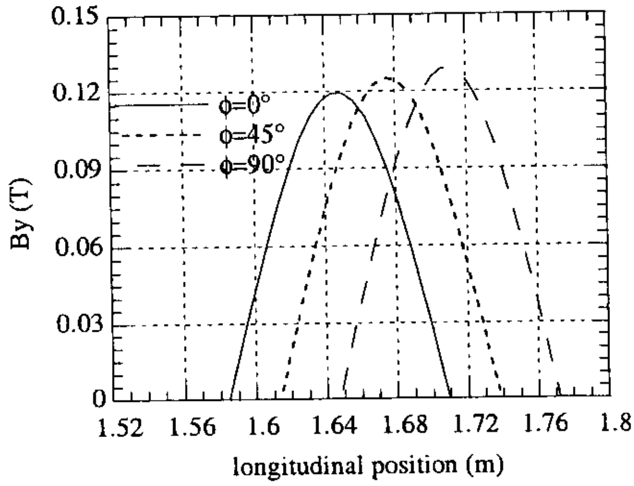

Fig.6. Phase effect on the peak fields.

Consequently, changing ϕ produces important closed orbit distortions. These have been cancelled during on-beam tests by the use of compensation coils installed on the main poles [7].

IV. CONCLUSION

OPHELIE, the first crossed overlapped electromagnetic undulator, was successfully tested in DC mode, on Super-ACO. Magnetic measurements perfectly fit the positron beam tests. Moreover these measurements have proved the total identity of H-undulator and V-undulator However, an unexpected orbit distortion was found due to the flux capture when the phase varies. For this reason, feedbacks on tunes and transverse position have been developed on the storage ring in order to reach the 1 Hz switching rate expected by the users in the near future.

Acknowledgements

Many thanks to LURE staff and especially to A. Nadji.

References

[1] A planar/helical electromagnetic crossed overlapped undulator at LURE, M. Corlier et al., MT 15 (1997), Vol. 1, 84-87.

[2] News on beam dynamics at Super-ACO, P. Brunelle et al., PAC 99, 1569-1571.

[3] A versatile electromagnetic planar/helical crossed undulator optimized for the SU5 low energy/high resolution beamline at Super-ACO, L. Nahon et al., NIM A 396 (1997) 237-250.

[4] OPERA 2D & 3D Vector-Fields Ltd (England).

[5] Limitations on the pulsed-wire field measuring technique, R.W. Warren, NIM A 272 (1988), 257-263.

[6] Improvements of the pulsed wire method to measure undulators, F. Marteau et al., this conference.

[7] Commissioning of OPHELIE : the new electromagnetic crossed overlapped undulator at Super-ACO, M. Corlier et al., PAC (1999), 2686-2688.