OBSERVATION AND INTERPRETATION OF DYNAMIC FOCUSING EFFECTS INTRODUCED BY APPLE-II UNDULATORS ON ELECTRON BEAM AT SOLEIL

O. Chubar, P. Brunelle, M.-E. Couprie, J.-M. Filhol, A. Nadji, L.S. Nadolski,
Synchrotron SOLEIL, Gif-sur-Yvette, France

Abstract

The paper presents the results of electron beam closed orbit distortion (COD) and tune shift measurements performed on three different APPLE-II type undulators using horizontal local closed orbit bumps. In agreement with data from other storage rings, our results show that, when APPLE-II undulators are used in elliptical, linear-vertical or linear-tilted polarization modes, the measured tune shifts and COD can not be explained only by residual first-order focusing effects: taking into account the second-order, or dynamic focusing effects, is necessary. We describe a COD interpretation method allowing for straightforward comparison of the measured effects on electron beam with predictions from calculations and magnetic measurements. The observed dynamic effects are in good agreement with calculations performed using RADIA magnetostatics code.

INTRODUCTION

The effects of insertion devices (ID) on electron beam represent an important topic of machine studies for the 3rd generation synchrotron radiation sources, which typically operate with a large number of variable-polarization undulators used simultaneously at many beamlines. ID effects on electron beam can be classified following their dependence on the inverse of the electron energy [1]:

- first-order effects, resulting from imperfections of ID magnetic fields, e.g. deviation of the field integrals from zero within a range of transverse position;
- second-order, or dynamic effects, appearing due to variation of magnetic field with transverse positions in central part of an ID.

The first-order effects can be easily estimated from magnetic measurements on a conventional "field integral" (stretched wire or body-less coil based) magnetic bench [2]; the prediction of dynamic effects from magnetic measurements is less straightforward. On the other hand, since the dynamic effects are a "feature" of a perfect (magnetic error free) ID, they can be predicted by 3D magnetostatic calculations [3, 4]. For a shimmed ID, dynamic effects may produce more severe effect on electron beam than first-order effects [3].

In the next section, we briefly describe a method to correlate the electron beam COD, introduced by an ID, to both the residual field integrals and the dynamic effects. This method is then used for interpreting the experimental data obtained at SOLEIL for various operation modes of APPLE-II undulators.

INTERPRETATION OF COD FROM AN ID

The effect of an ID on the electron beam COD can be approximated by a sum of contributions from three different virtual thin lenses (or kicks) acting both in the horizontal and in vertical planes. Two of these kicks (#1 and #2) are assumed to be located at ID extremities – to simulate first-order effects; and the third one (#3) in the ID centre – to simulate dynamic effects. The vectors of the horizontal and vertical plane COD considered at locations of N beam position monitors (BPM), $\mathbf{\Delta X} \equiv [\Delta x_1\ \Delta x_2\ ...\ \Delta x_N]^{\mathrm{T}}$ and $\mathbf{\Delta Y} \equiv [\Delta y_1\ \Delta y_2\ ...\ \Delta y_N]^{\mathrm{T}}$, can be then represented as:

$$\begin{cases} \mathbf{\Delta X}(x,y) = \mathbf{R}_x \mathbf{\Delta\Theta}_x(x,y) + \mathbf{R}_{xd}\Delta\theta_{xd}(x,y) \\ \mathbf{\Delta Y}(x,y) = \mathbf{R}_y \mathbf{\Delta\Theta}_y(x,y) + \mathbf{R}_{yd}\Delta\theta_{yd}(x,y) \end{cases} \quad (1)$$

where $\mathbf{\Delta\Theta}_{x(y)}(x,y) \equiv [\Delta\theta_{x(y)1}(x,y)\ \ \Delta\theta_{x(y)2}(x,y)]^{\mathrm{T}}$ are vectors of the two horizontal (vertical) kicks simulating the first-order effects, $\Delta\theta_{x(y)d}(x,y)$ are scalar values of the virtual kicks "responsible" for the dynamic effects; $\mathbf{R}_{x(y)} \equiv \{r_{x(y)ij}\}$ and $\mathbf{R}_{x(y)d} \equiv \{r_{x(y)i3}\}$ ($i = 1,2,...N$; $j = 1,2$) are respectively the $N \times 2$ matrices and N-vectors with the elements defined by the electron beam lattice functions $\beta_{x(y)}(z)$, $\eta_{x(y)}(z)$ and the betatron phase function $\varphi_{x(y)}(z)$ values at the locations of the BPM ($z = z_i$, $i = 1,2,...N$) and the virtual kicks ($z = z_j$, $j = 1,2,3$) [5]:

$$r_{x(y)ij} = \frac{[\beta_{x(y)}(z_i)\beta_{x(y)}(z_j)]^{1/2}\cos(|\varphi_{x(y)}(z_i) - \varphi_{x(y)}(z_j)| - \pi\nu_{x(y)})}{2\sin(\pi\nu_{x(y)})} + \frac{\eta_{x(y)}(z_i)\eta_{x(y)}(z_j)}{\alpha L} \quad (2)$$

with $\nu_{x(y)}$ being the horizontal (vertical) betatron tunes, α the momentum compaction factor and L the storage ring circumference. Provided that 3D magnetic field of a periodic ID is known, the virtual kicks simulating the dynamic effects can be estimated as [1, 4]:

$$\Delta\theta_{x(y)d}(x,y) = \frac{-e^2\lambda_u^3 N_u}{16\pi^2 m_e^2 c^2 \gamma^2}\partial_{x(y)}\sum_{n=1}^{\infty}\frac{B_{x\,n}^2(x,y) + B_{y\,n}^2(x,y)}{n^2} \quad (3)$$

where e and m_e are the charge and the mass of electron, c is the speed of light, γ is the reduced electron energy; λ_u is the ID period, N_u number of periods, $B_{x(y)n}$ the amplitudes of n-th harmonic of the horizontal (vertical) magnetic field components; $\partial_{x(y)}$ means partial differentiation over the horizontal (vertical) coordinate.

The virtual kicks describing first-order effects can be derived from the over-determined system of linear algebraic equations (1), with the COD data from a large number of BPM, e.g. using the linear least squares fit:

$$\begin{cases}\mathbf{\Delta\Theta}_x = (\mathbf{R}_x^{\mathrm{T}}\mathbf{R}_x)^{-1}\mathbf{R}_x^{\mathrm{T}}(\mathbf{\Delta X} - \mathbf{R}_{xd}\Delta\theta_{xd}) \\ \mathbf{\Delta\Theta}_y = (\mathbf{R}_y^{\mathrm{T}}\mathbf{R}_y)^{-1}\mathbf{R}_y^{\mathrm{T}}(\mathbf{\Delta Z} - \mathbf{R}_{yd}\Delta\theta_{yd})\end{cases} \quad (4)$$

The obtained kick values can be used for the estimation of the residual first and second magnetic field integrals:

$$\begin{cases} I_{y(x)1} = \pm\dfrac{m_e c\gamma}{e}(\Delta\theta_{x(y)_1} + \Delta\theta_{x(y)_2}) \\ I_{y(x)2} \approx \pm\dfrac{m_e c\gamma}{e}\lambda_u N_u \Delta\theta_{x(y)_1}\end{cases} \quad (5)$$

where "+" should be used for the vertical integrals (i.e. horizontal kicks) and "-" for the horizontal integrals (vertical kicks). The values from Eq. (5) can be directly compared with magnetic measurements data.

Alternatively, the effect of an ID on electron beam can be expressed in terms of betatron tune shifts [3]:

$$\Delta\nu_{x(y)}(x,y) = \frac{1}{4\pi}\overline{\beta}_{x(y)}\partial_{x(y)}\Delta\theta_{x(y)}(x,y) \quad (6)$$

where $\Delta\theta_{x(y)}(x,y)$ is the sum of the first- and the second-order kicks deduced from magnetic measurements (via Eq. (5)) and from modelling calculations (via Eq. (3)); $\overline{\beta}_{x(y)}$ are horizontal (vertical) beta-function values averaged over ID length.

EXPERIMENTAL RESULTS

In this section, we present the results of experimental study of the effects introduced by 3 different 80-mm period APPLE-II undulators (HU80) on the SOLEIL storage ring electron beam using horizontal closed orbit bumps. The orbit displacements were performed by means of a number of corrector magnets surrounding straight sections of interest. The attained range of the horizontal orbit displacement was -4.5 mm ≤ x ≤ 4.5 mm. For a set of orbit displacement values within this range, electron beam COD and betatron tune shifts were measured for different undulator polarization modes (i.e. for different parallel "phase" shifts of magnet arrays) at minimal vertical gap (15.5 mm). The interpretation of the measured COD data was done using Eqs. (2)-(5).

The results for the horizontal first field integral (vertical COD) are presented in Fig. 1. For all 3 undulators, we observe good agreement between the horizontal integrals obtained from the COD and those measured in the lab; the vertical second-order kicks calculated using RADIA code [6] and Eq. (3) appeared to be very small for any APPLE-II phase (parallel shift of magnet arrays).

The situation with the vertical field integral (horizontal COD) appeared to be more spectacular (see Fig. 2). Without taking into account dynamic effects, the interpretation of the horizontal COD measured for horizontal orbit displacements at non-zero APPLE-II phases resulted in very large vertical field integral values (dashed curves in the 2nd and 3rd row graphs in Fig. 2), which could not be related to the measurements performed on these undulators in the lab. However, with the dynamic effects taken into account by RADIA calculation and Eq. (3), the off-axis vertical field integral derived from the COD agrees much better with the one obtained from magnetic measurements. Figure 3 illustrates the results of independent measurements and interpretation of the same dynamic effects in terms of the horizontal tune shift. The tune shift measured for the quarter- and half-period APPLE-II phases are now in good agreement with the sum of predicted dynamic effects (by Eqs. (3), (6)) and first-order effects estimated from magnetic measurements.

Despite the fact that the dynamic focusing effects from APPLE-II undulators are clearly observable at SOLEIL, the storage ring performance is not directly affected.

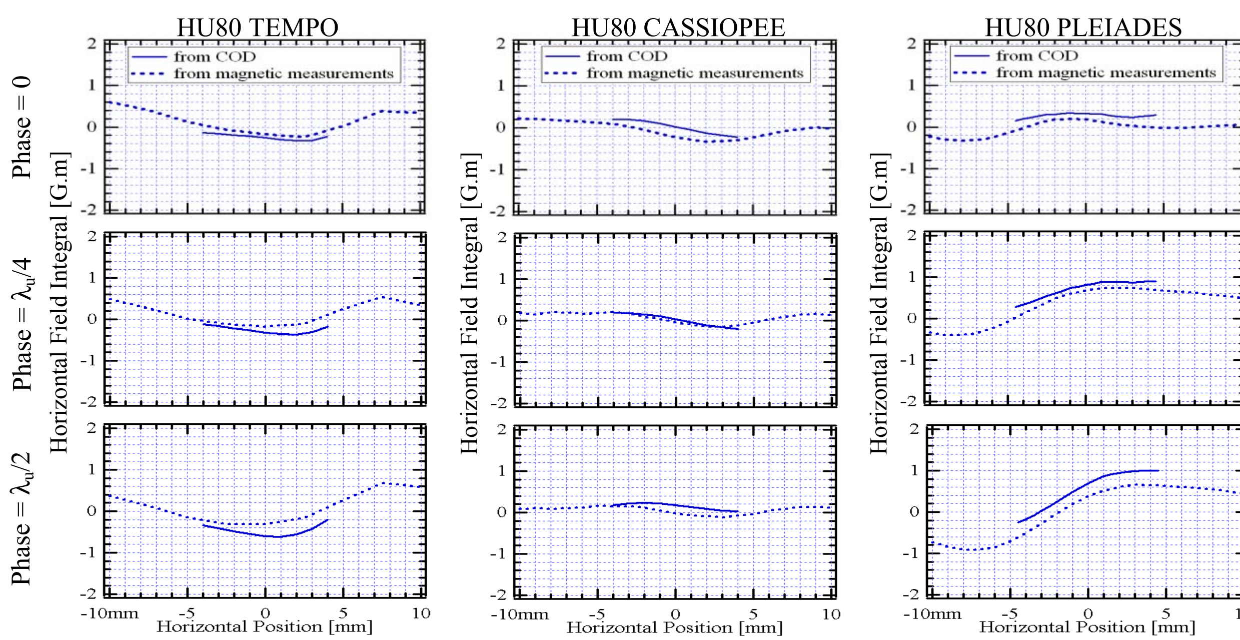


Figure 1: Horizontal first field integral vs horizontal position in the median plane for three HU80 APPLE-II undulators.

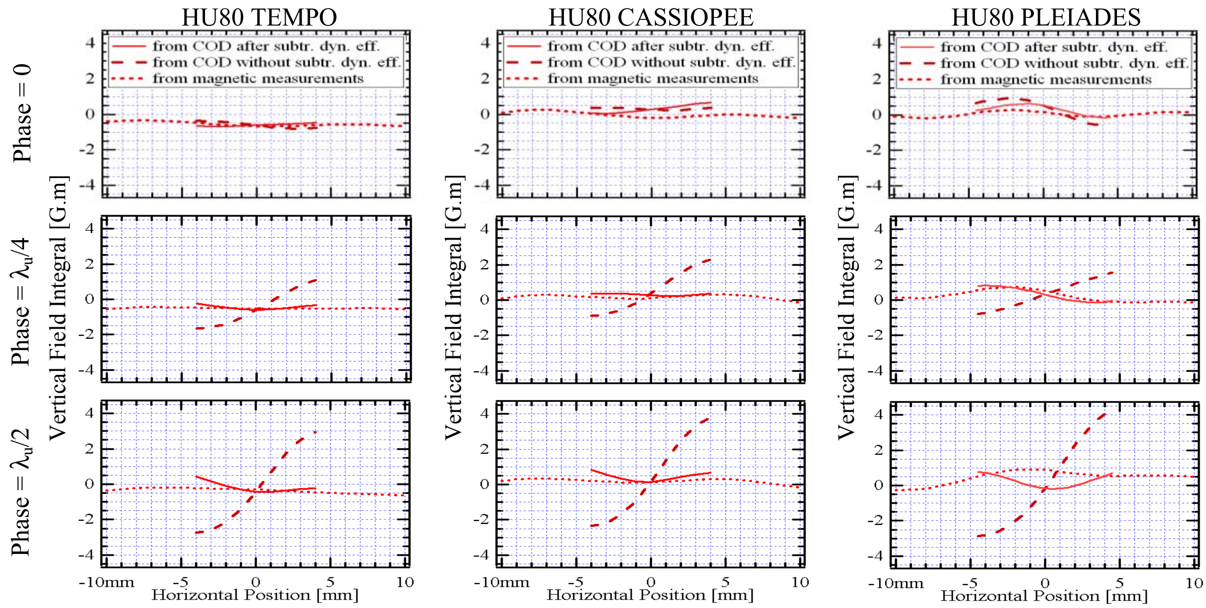
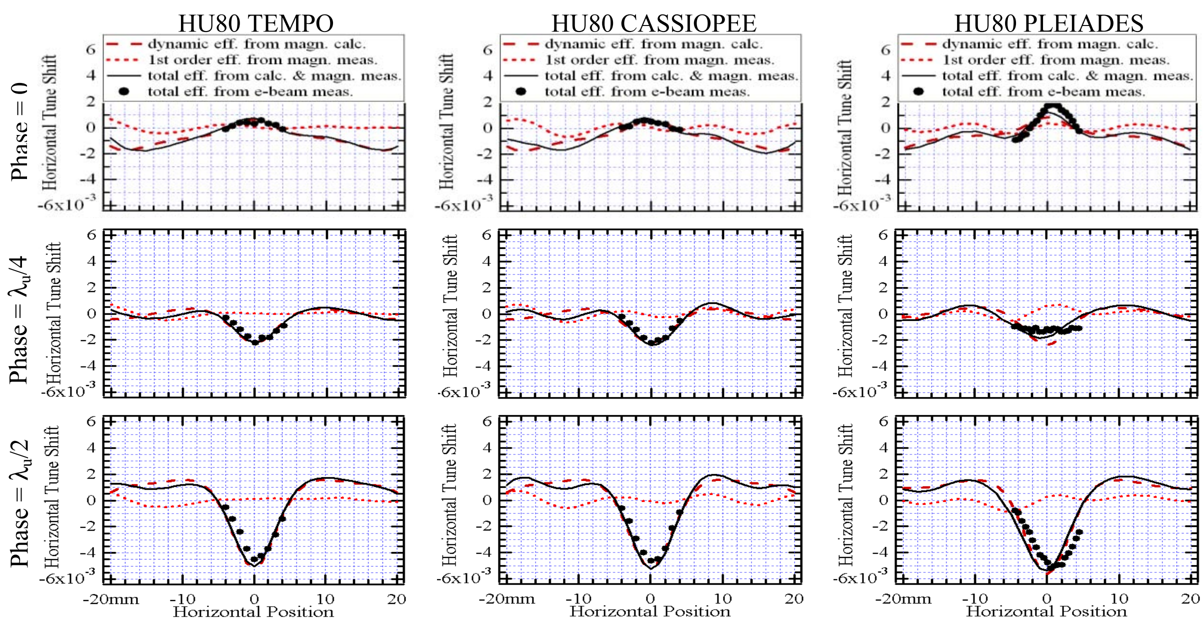


Figure 2: Vertical first field integral vs horizontal position in the median plane for three HU80 APPLE-II undulators.



Fi~ure 3: Horizontal tune shift as func'ion of horizontal ~osition for three HU80 APPLE-II undulators.

However, some reduction of injection efficiency occurs with HU80-PLEIADES being used at minimal gap and zero phase [7]. A possible explanation could come from the larger, compared to other HU80s, positive horizontal tune shift (and higher-order multipoles) introduced by this undulator at zero phase (see upper-right graph in Fig. (3)).

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