COMPENSATION OF VARIABLE SKEW- AND NORMAL QUADRUPOLE FOCUSING EFFECTS OF APPLE-II UNDULATORS WITH COMPUTER-AIDED SHIMMING

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Abstract

Variable (phase- and gap-dependent) skew- and normal-quadrupole focusing effects of APPLE-II undulators on electron beam are reportedly complicating practical use of this type of insertion devices in many synchrotron radiation sources. We show that these undesirable effects, whatever their physical “origin”, can be well controlled and in many cases efficiently compensated during the standard “virtual” shimming of APPLE-II undulators. Our method exploits small variations of the skew- and normal-quadrupole focusing components resulting from extra magnetic interaction, introduced by displacements of permanent magnet blocks during the shimming procedure, at different undulator phase and gap values. These variations can be calculated to a high accuracy, included into the corresponding “shim signatures” of magnetic field integrals, and used, along with undulator magnetic measurements data, for calculation of the most efficient magnet displacements. This approach is well suited for a computer-aided (e.g. genetic optimization based) shimming procedure. Practical results obtained with several APPLE-II undulators, which are currently successfully operating on the SOLEIL storage ring, are presented.

INTRODUCTION

“Virtual” shimming – i.e. shimming of permanent-magnet and hybrid insertion devices (ID) by small transverse displacements of individual magnets and/or magnet modules is currently used by many laboratories and commercial firms dealing with production of IDs [1-4]. Even though this shimming method has its limits, i.e. on the maximal “correctable” variation of the field integrals within a range of horizontal position [2], it can give very good results if used in combination with other techniques aimed to compensate magnetic field imperfections, such as magnet/module sorting in the process of ID assembling [1] and the correction of residual field integrals by “magic fingers” [5]. The “virtual” shimming can be easily automated, e.g. by using the simulated annealing [3] or evolutionary optimization approaches [4, 6].

At the “virtual” shimming of APPLE-II undulators, the effects related to magnetic interaction of permanent magnet blocks constituting the undulator structure are typically neglected: it is assumed that a small transverse displacement of a magnet block results in the same modification of the magnetic field integrals, whether this block is surrounded by other magnets or not [1-3]. In this paper, we show that small variations of the “virtual” shim efficiencies due to magnetic interaction altering with the longitudinal shift of magnet arrays (i.e. phase) can be calculated to high accuracy and exploited for the correction of undesirable phase-dependent variations of the field integrals and their transverse derivatives in an APPLE-II undulator. If, on the contrary, the magnetic interaction is neglected at the “virtual” shimming, this can generate or amplify undesirable phase-dependent effects.

In the next section, we present the results of calculation and measurement of the “shim signatures”, i.e. variations of magnetic field integrals associated with small transverse displacements of APPLE-II magnet blocks, for different values of the undulator phase. The subsequent section presents the examples of computer-aided shimming of SOLEIL APPLE-II undulators with the magnetic interaction taken into account.

“SHIM SIGNATURES” TAKING INTO ACCOUNT MAGNETIC INTERACTION

To calculate a “shim signature” with due regard for magnetic interaction, for a given ID operation mode or configuration, using a 3D magnetostatics code (e.g. RADIA [7]), a more-or-less complete ID model should be used (see Fig. 1). In such model, magnetic material properties should be assigned to different (segmented) magnet block volumes; and the model must be solved with respect to magnetizations in the sub-volumes. Only after this, the magnetic field and field integrals can be computed. For the calculations of the “shim signatures” related to each ID configuration, two versions of the model must be used: a “perturbed” one – with the magnet block of interest being displaced in space, and the original non-perturbed model. The “shim signatures” can be defined as differences of the magnetic field (field integrals) created by the “perturbed” and non-perturbed models.

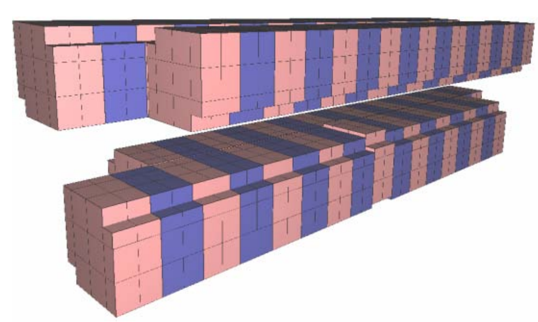

Figure 1: RADIA model of an APPLE-II undulator central part for calculating “shim signatures” at the parallel shift of magnet arrays equal to half undulator period.

Examples of the field integral "shim signatures" calculated using RADIA and measured at SOLEIL on ESRF-type body-less coil bench for a 80 mm period APPLE-II undulator (HU80) are presented in Fig. 2. The calculations and measurements were done in the horizontal median plane, for 15.5 mm vertical gap. The magnetic material of the blocks is NdFeB with the remnant magnetization ~1.25 T.

In addition to the main "shim signatures" (calculated and measured for zero undulator phase), Fig. 2 also shows differences between the "signatures" obtained for the half-period phase and for the zero phase (continuous lines and black solid circles). These differences result from magnetic interaction altering with the undulator phase. We note good agreement between the results of the calculations and measurements both for the main "shim signatures" and their phase-dependent variations.

Phase-dependent effects on the field integrals are also present at transverse displacements of longitudinally-magnetized blocks. In that case, maximal variation of the field integrals happens at the phase equal to quarter undulator period.

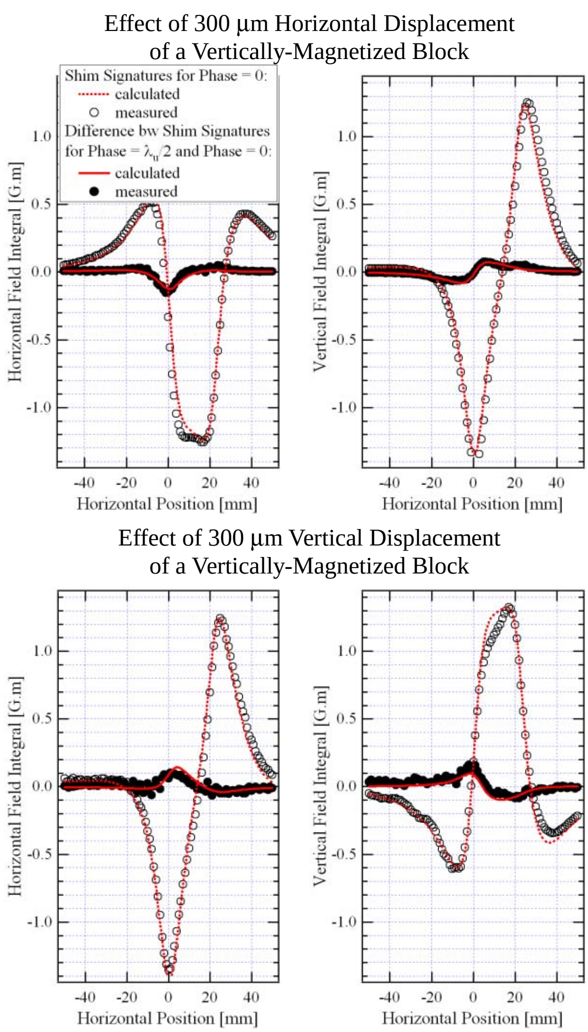

Figure 2: Field integral "shim signatures" calculated and measured for different parallel shifts of magnet arrays of HU80 APPLE-II undulator.

COMPUTER-AIDED SHIMMING

Even though for a single magnet displacement the phase-dependent effects are not very strong compared to the main effects (see Fig. 2), a total result of a large number of magnet displacements (shims) can be quite significant. To make sure that the phase-dependent effects don't cause undesirable extra variations of the field integrals and the associated multipoles, and to be able to use these effects for corrections of existing undulator field imperfections (e.g. phase-dependent skew-quadrupole [8]), one has to take them into account during the shimming.

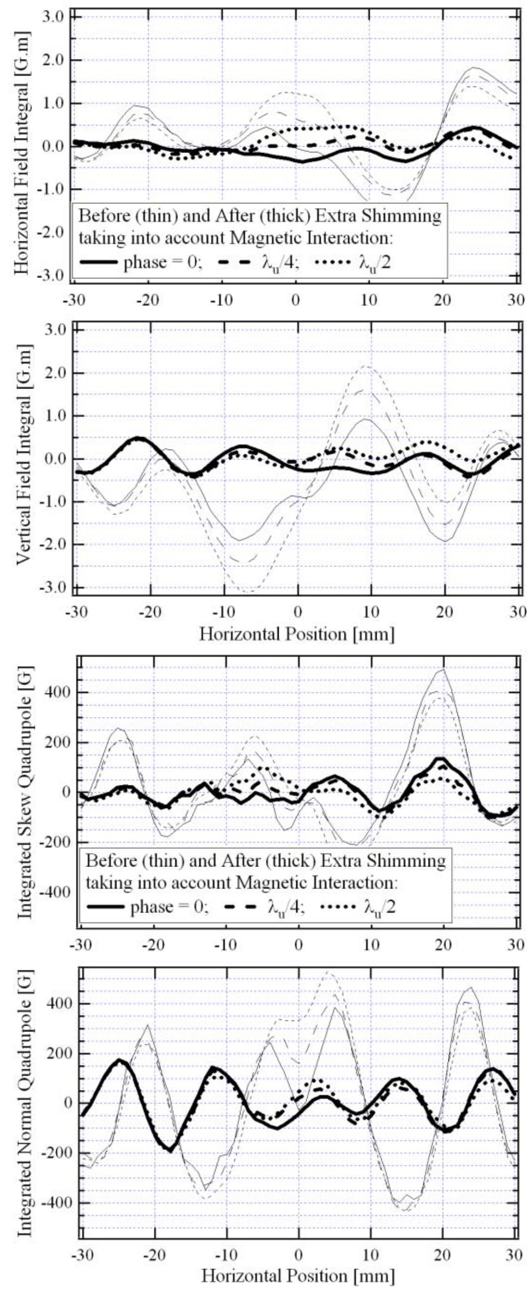

Figure 3: Horizontal and vertical field integrals and their derivatives over horizontal coordinate (i.e. integrated skew- and normal quadrupoles) before and after extra shimming of HU80-µFoc aimed to reduce the quadrupole dependence on phase.

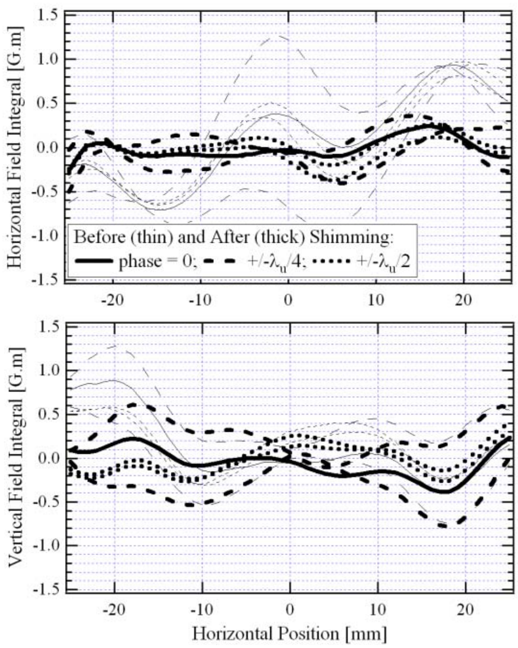

Figure 4: Horizontal and vertical field integrals before and after "virtual" shimming of HU52-LUCIA.

This may mean a significant complication if the shimming is performed empirically by human expert, however, this doesn't represent any problem for a computer-aided shimming procedure [4, 6]. In such approach, the magnetic interaction effects can be easily taken into account by using the "shim signatures" calculated for different phases, together with the magnetic measurements data obtained for the same phases. This increases the amount of information which has to be used at the shimming and requires adding extra sub-terms into the general goal function, as well as the associated "weights" in user interface; however, this doesn't increase the overall complexity of the method and in most cases doesn't affect the optimization efficiency.

In the optimization process, it may happen that a reduction of phase-dependent skew- and / or normal quadrupole can be achieved only for the expense of certain increase of the field integral deviation from zero (within a range of horizontal position), which no longer depend on phase. Since this type of field integral imperfection can be easily corrected by "magic fingers" [5], one may accept it during the "virtual" shimming. This can be fine-tuned by the corresponding optimization "weights". A more sophisticated approach can be based on multi-objective optimization, which can be efficiently combined with genetic algorithms [6].

Figures 3 and 4 show the results of shimming of two different SOLEIL APPLE-II undulators. The 80 mm period undulator HU80-μFoc has been first shimmed without taking into account the magnetic interaction. Such shimming had left relatively large residual field integrals off the electron beam axis and very strong (~400 G) variation of the integrated on-axis normal quadrupole with the phase (thin curves in Fig. 3). This undulator has been therefore partially de-shimmed and then re-shimmed taking into account the magnetic interaction at calculation of the "shim signatures". After this, "magic fingers" were also re-adjusted. The results of this extra shimming are shown by thick lines in Fig. 3. We emphasize substantial reduction of the normal quadrupole variation with the phase (see lower graph in Fig. 3).

In the other example (see Fig. 4), after the optimized modular assembling of 52 mm period APPLE-II undulator HU52-LUCIA, relatively small values of the residual horizontal and vertical field integrals were obtained (less than 1.5 G m in absolute, which is a good result for a just assembled undulator); however the variation of the horizontal field integral with the phase appeared to be very large, with the maximal deviations occurring at quarter-period anti-parallel shift of magnet arrays (thin dashed curves in the upper graph in Fig. 4). In the process of shimming by displacements of longitudinally-magnetized blocks (made with the primarily goal to decrease the radiation phase error), it became possible to reduce the undesirable variation of the horizontal field integral (down to ~20 G cm; thick curves in Fig. 4). We note that this reduction of the horizontal field integral was obtained by the same transverse displacements of magnet blocks, which allowed to decrease the RMS radiation phase error from ~6 to ~2.5 degree.

The results presented above were obtained with the help of "IDBuilder" – a genetic algorithm based computer code for sorting and shimming of undulator magnets [6].

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