STUDIES OF THE NONLINEAR DYNAMICS EFFECTS OF APPLE-II TYPE EPUs AT THE ALS*

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Abstract

Elliptically Polarizing Undulators (EPUs) have become more and more popular at synchrotron radiation sources, providing full polarization control of the photon beam. The fields of the most commonly used APPLE-II type EPUs have a very fast, intrinsic field roll-off, creating significant non-linearities of the beam motion with in some cases large impact on the dynamic (momentum) aperture. In general, the nonlinear effects get stronger with longer periods and higher undulator magnetic fields. One of the planned future beamlines at the ALS (MERLIN) will use a quasiperiodic EPU with 9 cm period and maximum B fields of about 1.3 T. We will present simulation studies for the proposed shimming schemes for this future device to reduce the nonlinear effects to acceptable values, as well as experimental studies for the existing 5 cm period EPUs already installed in the ALS.

INTRODUCTION

The ALS has successfully installed a number of APPLE II-type [1] elliptically polarizing undulators (EPU's) [2], capable of generating high-brightness photon beams with variable linear, and elliptical or circular polarization characteristics. The existing devices have a period of 50 mm. A 90 mm period device is currently being designed and fabricated for the new ultrahigh-resolution MERLIN beamline now under construction. The interaction of the existing devices with the stored electron beam has been intensely studied at the ALS, particularly the polarization-dependent beam dynamics effects. Those studies have been aided by the fact that the dynamics and the lattice of the ALS without EPUs are very well understood and characterized. The effects can be attributed to three distinct sources:

1. The original ALS EPU end design was developed to provide steering- and displacement-free behavior for all row-phase and gap configurations, assuming $\mu = 1$ permanent magnet material; however, the non-unity relative permeability, $\mu \approx 1.15$, of the magnetic blocks introduces a row-phase dependent dipole (steering) field; this effect has been significantly reduced for the most recent EPUs by introducing an optimized end design [3, 4]. For older devices a fast feedforward system with multidimensional correction tables was implemented.
2. A shift-dependent skew quadrupole term was found to emanate from micrometer-level magnetic force induced non-random motion of permanent magnet blocks. Trim coils were installed on the vacuum chambers of the existing EPU's to allow for feedforward compensation of skew quadrupole fields [5]. For future devices the mechanical design will be changed to eliminate the magnetic force induced correlated motion of blocks.
3. EPUs intrinsically exhibit a fast transverse roll-off of their magnetic fields, particularly in vertical polarization mode. Combined with the undulating motion of the beam this gives rise to so-called dynamic multipoles affecting both the linear focusing as well as the nonlinear transverse dynamics. Beam-based measurements and simulations show that the transverse dynamic aperture of the ALS beam is reduced by EPU fields, and that the reduction is shift-dependent. The effect is noticeable with existing ALS operations, but,if uncompensated, will become intolerable for top-off operation, when electrons will be injected with large offsets with the EPUs in operation.

Basic design modifications are being implemented on the MERLIN EPU (MEPU) to address the first two issues. The dynamic aperture concern, however, is significantly exacerbated by the long period of the MEPU. Because the dynamic multipole effects scale like $1/E^2$, they are also much more important in the ALS, which is a relatively low energy light source (1.9 GeV), compared to higher energy machines like the ESRF. To address the issue we have performed detail magnetic and tracking analysis of a passive correction method first proposed at the ESRF [6] and later successfully tested at BESSY [7].

DYNAMIC FIELD INTEGRALS

It is well known that undulator fields have focusing / defocusing effects on passing electrons. The effect is not seen in integrated fields; it stems from variations in field strength as seen by a periodically wiggling electron passing through the structure. An ideal focusing element will provide an angular deflection proportional to the ray offset. Fig. 1 shows the deflection angle for particles tracked through the MEPU device. The strongly nonlinear behavior for large (>5mm) particle offsets—similar in shape and effect to the force of the beam-beam interaction in colliders—results in a reduced dynamic aperture, whereas the large slope for smaller amplitudes corresponds to horizontal defocusing, affecting the betatron tune and lattice symmetry. In the

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ALS the defocsuing effect is compensated using several neighbouring quadrupole magnets, whereas the compensation of the nonlinearity with conventional multipole magnets would be extremely difficult, because of the rich harmonic content of the field.

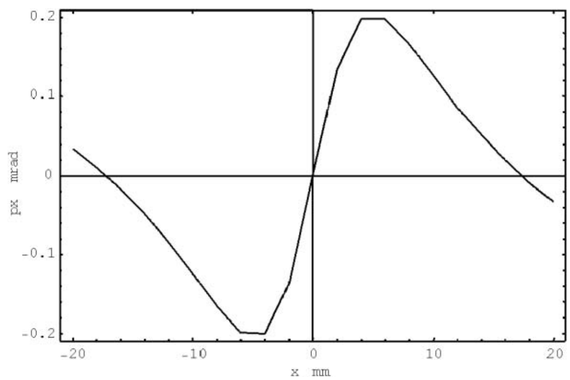

Figure 1: Angular deflection at the exit of the MEPU device operating in linear vertical polarization mode, based on particles with initial location (x,y=0). Tracking was performed using Radia [8] and independently verified using using Cosy [9].

MEASURED IMPACT ON GLOBAL NONLINEAR DYNAMICS

The impact of the dynamic multipoles emanating from the EPUs at the ALS can be seen already for the existing 5 cm period devices, particularly in vertical polarization modes at low photon energies. A single installed EPU can reduce the Touschek dominated beam lifetime (dynamic momentum aperture) by up to 30%. Even more importantly for top-off operation, the injection efficiency could be degraded from close to 100% to significantly below 50%. Using measured frequency maps, one can clearly see the effects of the dynamic multipoles. Fig. 2 shows two frequency map measurements: One of them with all insertion devices open. The other one with a 5 cm period EPU at minimum gap in vertical polarization mode.

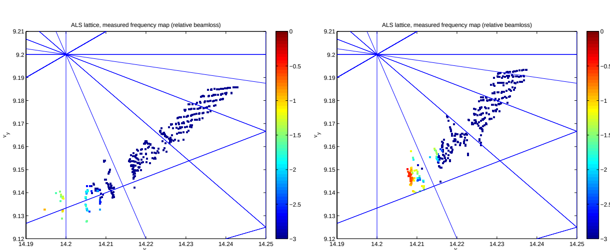

Figure 2: Measured frequency maps for the ALS with insertion devices open, as well as one 5cm period EPU closed to minimum gap in vertical polarization mode. Measurement points are spaced equally in betatron amplitude space and the colorcode of the points indicates the fraction of beam loss on a logarithmic scale.

One can clearly see that the shape of the tune footprint in both cases is different. Particularly the tune shift with horizontal amplitude is modified and becomes nonlinear with the EPU in vertical polarization mode. In addition, more resonances are excited and significant beam losses occur at lower amplitudes (red areas).

DESIGN OF CORRECTION SHIMS

To address the dynamic multipole issue, passive shims have been proposed [6] that act to linearize the angular kick with displacement over a broad range of phase-shift modes of operation. The shims are small pieces of magnetic steel, about 4 mm wide, 100-200 micrometers thick, extending the length of a block, and located on the beam-side face and inner wall of certain blocks (see Fig. 3). One of their potential disadvantages is that their effect scales like $1/E$, whereas the dynamic multipoles scale like $1/E^2$. However, since the ALS operates nearly all the time at one beam energy, this is not a serious effect for us.

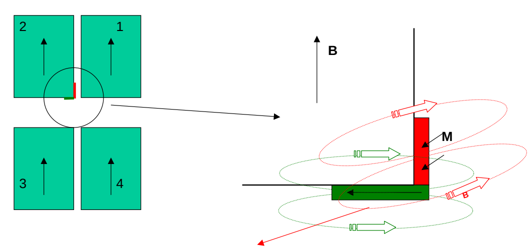

Figure 3: Sketch of passive magnetic steel shim (left), and the magnetization and resulting fields they produce. A combination of such shims, appropriately distributed on different blocks in all four quadrants, can produce fields that compensate for the nonlinear dynamic focusing.

Detailed Radia [8] models were used to optimize the shim sizes, number and distribution among the four MEPU quadrants so as to maximize the dynamic aperture for all polarization modes. Based on detailed tracking simulations, the final distribution of shims will provide sufficient dynamic aperture for operation in Top-Off mode in all elliptical modes and in vertical and horizontal polarization modes; variable linear modes around 45^o will not be allowed. This restriction is acceptable for the physics of interest to the MERLIN beamline.

As an example, Figure 4 shows the angular kick produced on the beam by the MEPU after shimming. Note the mostly linearized profile field dependence and the factor $\approx$3 reduction in amplitude compared to that of the uncorrected case in Fig.1.

Calculations were also carried out to verify that the correction works not just at minimum gap but also for smaller fields. In the case of the MEPU these simulations show that the shims (for the polarization modes mentioned above) are effective enough for all gaps, so that injection efficiency and beam lifetime should not be significantly impacted.

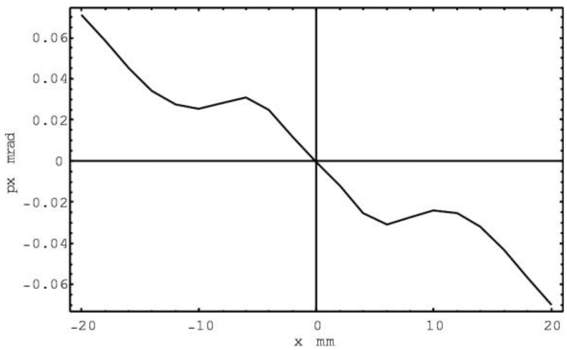

Figure 4: Angular deflection in linear vertical polarization mode with optimized shims. Note the difference in vertical scale and the 60% reduction in peak angular kick, as well as the nearly linear dependence of angle on offset.

EFFECTIVENESS OF SHIM CORRECTION

Fig. 5 is a simulated frequency map of the shimmed device operating in linear vertical polarization mode, suggesting injection at ≈10 mm offset during Top-Off should be acceptable. As is the case for the existing unshimmed EPUs, adjacent normal quadrupoles will be used to compensate for the (linear) focusing effects.

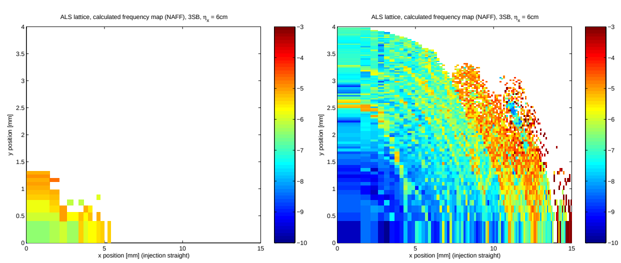

Figure 5: Increase in dynamic aperture predicted for the 9cm MERLIN EPU. Left side: Dynamic aperture for vertical polarization setting at minimum gap if device would be installed without shims. Right side: with shims. The color code of the plots indicates the tune diffusion rate on a logarithmic scale. The dynamic aperture in the case with shims is nearly the same as the one for the nominal ALS lattice with realistic (small) machine errors.

Beam-based measurements and simulations suggest that shimming will also be required for the EPU50 devices for Top-Off operation, although the reduction in dynamic aperture is not as severe as for the MEPU device. The analysis work developed for the MEPU has also been applied to the existing EPU50 devices at the ALS. An optimized set of shims has been developed. Calculations predict that this shim set will allow to make the EPU50 devices virtually transparent in all polarization modes. It will be tested on the EPU50s in the next few months to validate the design concept and optimization process in anticipation of Top-Off operation.

CONCLUSIONS

Dynamic multipoles created by the interplay of the undulating trajectories with the intrinsic transverse field roll-off of APPLE-II type EPUs have important impact on the beam dynamics at the ALS. The linear effect can be compensated well using lattice quadrupoles. The nonlinear effects reduce the dynamic aperture substantially, especially for planned future devices with longer periods and higher fields. To correct for this effect, a passive shimming scheme has been adopted, guided by earlier work at ESRF and BESSY. Simulations show that with those optimized shims, most of the dynamic aperture reduction can be recovered and operation of the long period EPUs should be possible for all gaps and most polarization modes. Detailed frequency map measurements were carried out for the existing 5 cm period EPUs in the ALS. The results agree quantitatively with tracking simulations. Shims for those devices have been designed and will be tested within the next months.

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