CONTROL OF NONLINEAR DYNAMICS BY ACTIVE AND PASSIVE METHODS FOR THE NSLS-II INSERTION DEVICES*

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Abstract

Nonlinear effects from insertion devices are potentially a limiting factor for the electron beam quality of modern ring-based light sources, i.e., the on and off-dynamical aperture, leading to reduced injection efficiency and beam lifetime. These effects can be modelled by e.g. kick maps ($\sim 1/\gamma^2$) and controlled by e.g. first-order thin or thick magnetic kicks introduced by "magic fingers," "L-shims," or "current strips". However, due to physical or technological constraints, these corrections are typically only partial. Therefore, a precise model is needed to correctly minimize the residual nonlinear effects for the entire system. We outline a systematic method for integrated design and rapid prototyping based on evaluation of the 3D magnetic field and control of the local trajectory with RADIA, and particle tracking with Tracy-3 for validation. The optimal geometry for the compensating magnetic fields is determined from the results of these simulations using a combination of linear algebra and genetic optimization.

MOTIVATION

Medium-energy synchrotron radiation sources have to accommodate large number of IDs (Insertion Devices) producing bright radiation in different spectral ranges, from UV and soft X-rays to hard X-rays.

In UV and soft X-ray range, variable polarization is often required; whereas in hard X-ray range, linear-horizontal polarization is usually sufficient. Two popular types of ID: Elliptically Polarizing Undulator (EPU) (APPLE-II and electro-magnetic device) and In-Vacuum Undulator (IVU) have proved to satisfy well these user requirements for soft and hard X-ray ranges respectively. Unfortunately, IDs, and in particular EPUs, because of their intrinsic magnetic design features, can have considerable impact on electron beam dynamics in modern ring-based light sources. This impact can potentially become more "visible" for the optimized low-emittance sources, such as NSLS-II.

In this paper, we focus on simulations for EPUs, because of their potentially stronger impact on electron beam dynamics; however, the approach and methods that we describe in the following sections, are applicable to other types of IDs.

BEAM DYNAMICS MODEL

The computer model for the lattice evaluates the Poincaré map

$$\bar{x}_n = \mathcal{M}^n \bar{x}_0 \qquad (1)$$

The RADIA kick map [1] for one ID period

$$\mathcal{M}_k p_{x,y} = p_{x,y} - L\,\partial_{x,y}\langle H_k\rangle_\lambda \qquad (2)$$

is generated by the Hamiltonian [2-3]

$$\langle H_k\rangle_\lambda = \frac{1}{2(1+\delta)}\left(\left\langle\left(\frac{q}{p_0}\int_s B_y(z)dz\right)^2\right\rangle_\lambda + \left\langle\left(\frac{q}{p_0}\int_s B_x(z)dz\right)^2\right\rangle_\lambda\right) + O(p_{x,y}^4) \qquad (3)$$

averaged over a period length λ. The kick

$$\Delta\theta_{x,y} = \Delta p_{x,y}/(1+\delta) \qquad (4)$$

scales with the ID length L and λ^2. It is second order in γ whereas a correction kick is linear.

Hence, to correctly model an ID with current strips or other type of corrections in our beam dynamics code, and for a straightforward approach to exchange models with the ID designers, we implemented a symplectic integrator that works directly on the 3D field maps ($\bar{B}(x,y,z)$) resulting from magnetic simulations and/or measurements. We also included the radiation effects by generalizing the Hamiltonian flow to a vector field so that e.g. the equilibrium emittance can be evaluated.

MAGNETIC MODEL

EPU Design

At NSLS-II a systematic approach has been developed to optimize the parameters of IDs [4]. For an EPU, it is driven by the beamline spectral requirements and the magnetic structure performance in different polarization modes at a given minimal gap. The magnetic optimization depends on multiple variables (polarization mode, magnet geometry, magnetic material), therefore this step strongly relies on RADIA, a fast and accurate 3D magnetostatic computer code [5]. Figure 1 presents the fundamental photon energy vs. period dependencies for the main polarization modes, assuming 16 mm minimal vertical gap and square NdFeB (Br = 1.25 T) magnet blocks of two different sizes, 30 mm and 38 mm. A 49 mm period was chosen by the NSLS-II Soft Inelastic X-ray Scattering (SIX) beamline based on its spectral requirements for different polarizations.

Nonlinear Corrections

The same magnetic model is used to accurately predict the effects of IDs on the electron beam; a good agreement with experimental measurements has been observed at SOLEIL [6]. These effects will be corrected by mean of thin current sheets disposed along the magnetic gap; this approach was first proposed by Ingvar Blomqvist and successfully implemented at BESSY-II [7]. An efficient approach has been developed to optimize the currents in

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the sheets. The current distribution J applied to the current foils is the least-squares solution of

$$I = QJ \quad (5)$$

where I is the first field integral derived from the second order kick $\Delta\theta$ given in Eq. (4) and Q the matrix with elements representing field integrals from different strip conductors of a given cross section at given locations for 1 A of current.

Fig. 2 compares the field integral created by 40 current sheets to the second order kick for the 6 m long EPU of the SIX beamline in the horizontal mid-plane. The field integrals match well, however these corrections are never perfect especially off the mid-plane. Therefore beam dynamics modelling and simulations have to be included into the optimization loop.

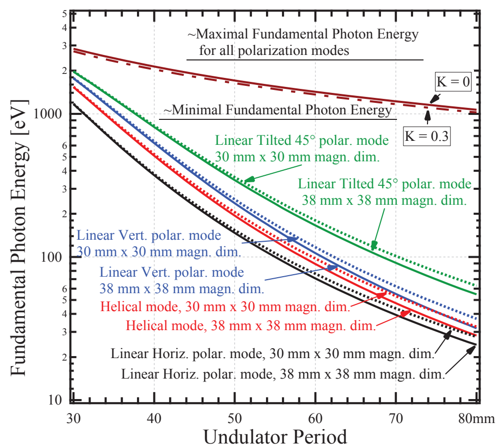

Figure 1: Minimal and maximal fundamental photon energy of radiation produced by APPLE-II type undulators in long straight section of the 3 GeV NSLS-II storage ring; main polarization modes considered as functions of period for two different cases of magnet transverse dimensions.

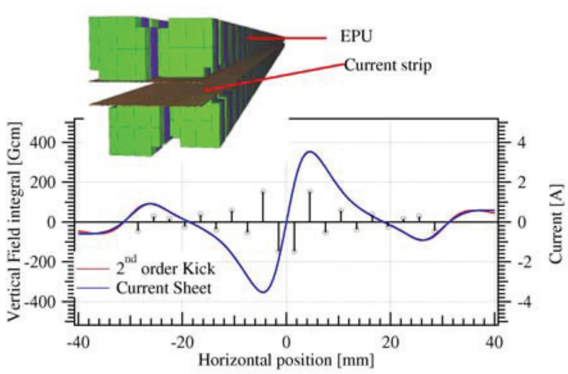

Figure 2: Second order kick in the horizontal mid-plane created by a 6 m long APPLE-II undulator in linear vertical polarization mode and field integral generated the 40 current strip (6.5 m long, 2 mm wide, 0.3 mm thick and 1 mm space).

TRACKING RESULTS

The baseline tune footprint is shown in Fig. 3 and the frequency maps for on and off-momentum dynamic aperture in Figs. 4-5, respectively. The EPU49 hor./ver. kick maps are shown in Figs. 6-7 and the corrected in Figs. 8-9. We essentially have full control in the hor. plane and the linear gradient in the ver. is reduced by about a ×2. The impact of EPU49 (6 m) in two long straights is shown in Fig. 10. And with current strip corrections in Fig. 11. Due to limited space, we are only showing the on-momentum results. To summarize, with the current strip corrections, the frequency maps for on and off-momentum dynamic aperture are essentially restored to the baseline level.

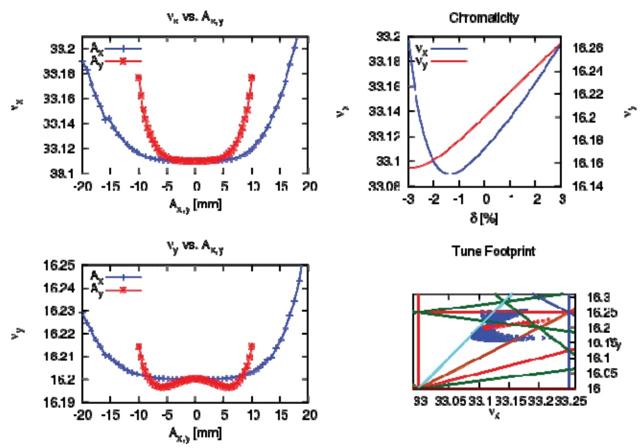

Figure 3: Baseline Tune Footprint.

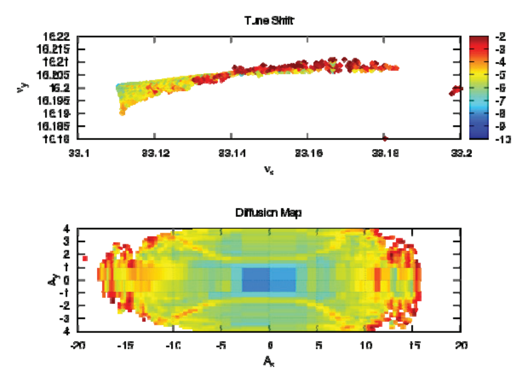

Figure 4: Baseline On-Momentum Frequency Map.

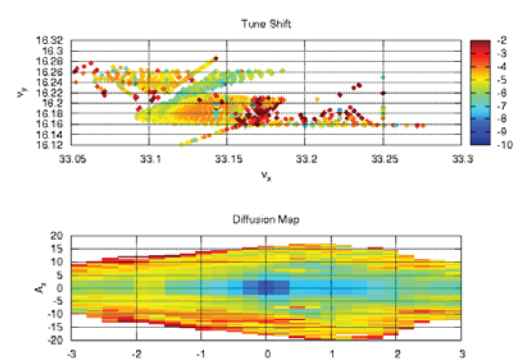

Figure 5: Baseline Off-Momentum Frequency Map.

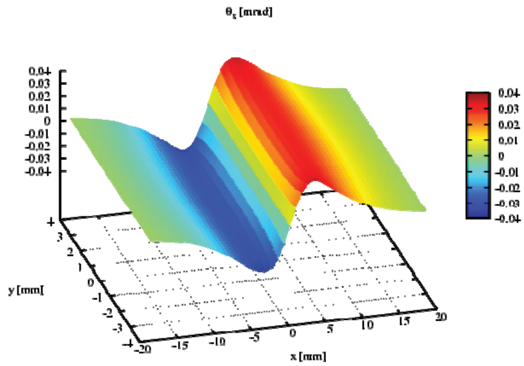

Figure 6: EPU49 Horizontal Kick Map.

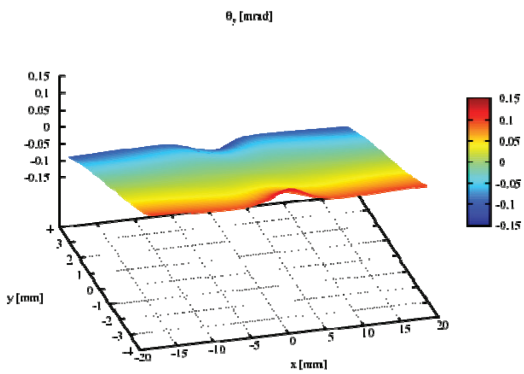

Figure 7: EPU49 Vertical Kick Map.

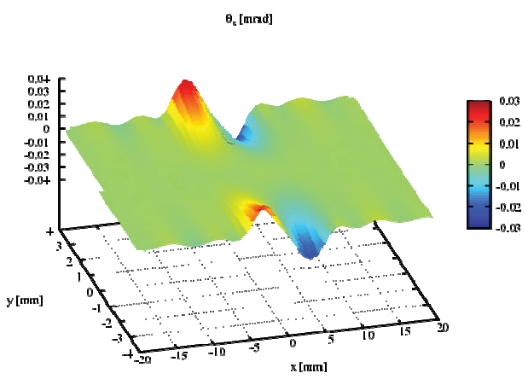

Figure 8: EPU49 Corrected Horizontal Kick Map.

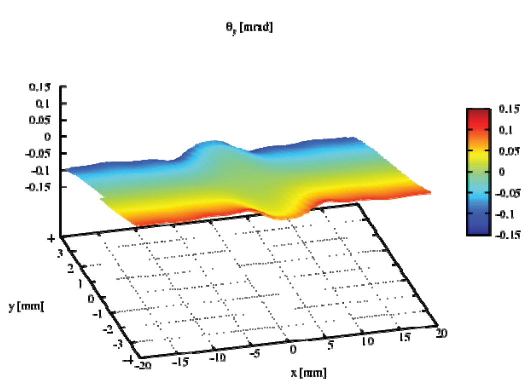

Figure 9: EPU49 Corrected Vertical Kick Map.

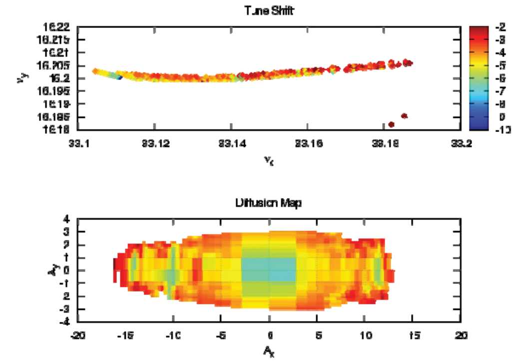

Figure 10: Impact on On-Momentum Frequency Map from EPU49 (6m) in Two Long Straights.

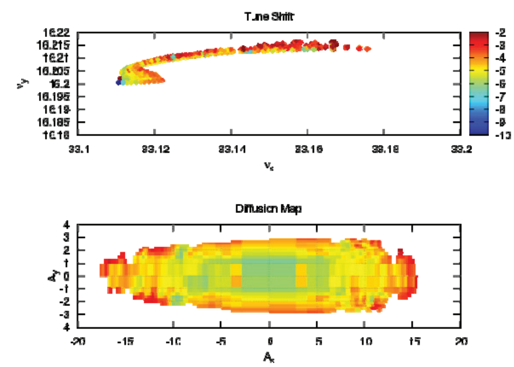

Figure 11: Impact on On-Momentum Frequency Map from Corrected EPU49 (6m) in Two Long Straights.

CONCLUSIONS

We have outlined and demonstrated an integrated approach for the design and control of the nonlinear impact from Insertion Devices.

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