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COMPENSATION OF INSERTION DEVICE INDUCED EMITTANCE VARIATIONS IN ULTRALOW EMITTANCE STORAGE RINGS*

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Abstract

With the advent of multi-bend achromat lattices, extremely low emittances are to become the norm in storage ring-based X-ray photon sources. In these lattices, the ratio of beam energy lost to radiation in the insertion devices (IDs) to the overall beam energy loss is larger relatively than in 3rd generation light sources. As a result, these machines are more sensitive to the energy loss variations occurring as the users operate variable-gap IDs and to the concurrent variations in radiation damping time, equilibrium emittance, and ultimately transverse properties of the beam. With possibly tens of variable gap IDs continuously and independently varying their gaps to meet the experiment needs, the resulting variation in emittance and beam sizes can be significant and can jeopardize the experimental performance in some of the beamlines. In this paper we describe and discuss possible methods for compensating such emittance variations and maintaining constant transverse beam properties for the experiments.

INTRODUCTION

In the last ten years, the field of ring-based synchrotron light sources has been characterized by the transformative revolution driven by the advent of multi-bend achromat (MBA) lattices. Technological progress and improved beam dynamics calculation techniques made the development and construction of storage ring using such lattices realistic, and as a result, a number of upgraded and new light sources based on MBA schemes were proposed worldwide and in several cases funded. The recent successful commissioning and first operation of MAX IV in Sweden [1] demonstrated the feasibility of these schemes and provided confidence for the incoming projects.

The several orders of magnitude brightness improvement promised by MBA rings is based on their capability of reducing their equilibrium emittance by more than an order of magnitude with respect to most of the present 3rd generation light sources. This is obtained by a combination of strong transverse focusing and large bending radii in dipole magnets to control and reduce dispersion in the arcs. A consequence of the large bending radius is the decrease of the energy radiated in the bending magnets which can now become comparable to the usually much smaller energy radiated in insertion devices (IDs). In this situation, and differently from the case of 3rd generation light sources, IDs significantly contribute to radiation damping and hence in defining the equilibrium emittance of the ring.

During operation, ID gaps are independently moved and controlled by users according to their needs. In MBA lattices this can generate large random variations of the emittance [2] and of the transverse distribution of the electron beam and ultimately of the photon beam in the beamlines - this is especially true for short wavelengths, where far from diffraction, the photons follow the electron distribution with fidelity.

Some of the beamline experiments, such as for example those based on scanning transmission X-ray microscopy (STXM), are very sensitive to variations of the transverse photon distribution and the quality of their experiments can be significantly affected by them.

In this paper we discuss possible techniques that could be used to compensate for these ID-induced emittance variations in ultra-low emittance MBA lattices.

A PARTICULAR LATTICE EXAMPLE

In order to evaluate the different emittance compensation schemes we will use ALS-U lattice v18.127. This is an obsolete lattice (the ALS-U project is presently using version v20 of this lattice [3]) but it is representative of the typical MBA lattice. Figure 1 shows the 9-bend cell and the optical functions for the lattice and Table 1 summarizes its relevant parameters.

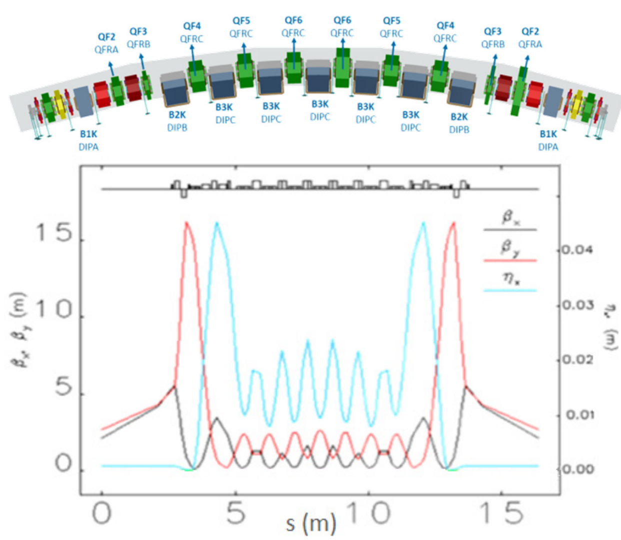

Figure 1: Layout and optical functions of the (obsolete) ALS-U 9-BA v18.127 lattice used for the evaluation of the emittance compensation techniques.

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Table 1: ALS-U (obsolete) Lattice v18.127 Parameters

Parameter	Value	Unit
Energy	2	GeV
Number of bends per period/ number of periods	9/12	
RF frequency	500	MHz
Harmonic number	328	
Charge per bunch	1.15	nC
Total average current	500	mA
Bend radius/gradient/angle	8.6/-7/3.$\overline{3}$	m/m^{-2}/deg
Natural emittance	109	pm
Hor./Vert. emitt. with IBS at full coupling	81.3/81.3	pm
R.m.s. bunch length with IBS and harmonic cavities	14.6	mm
Energy spread	0.083	%
Energy lost/turn (no IDs)	181.9	keV
Hor. partition number	1.865	
Momentum compaction	2.68 x 10^{-4}	

Figure 2 shows the result of an ELEGANT [4] simulation showing that for example, a 20 keV energy loss induced by IDs decreases the emittance in each plane by ~5 pm equivalent to ~6% of emittance reduction.

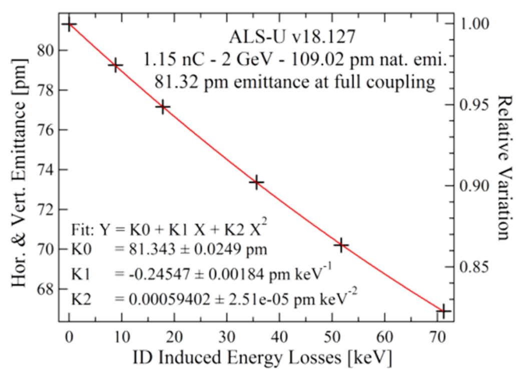

Figure 2: Simulation showing the emittance dependence on ID-induced losses for the ALS-U v18.127 lattice.

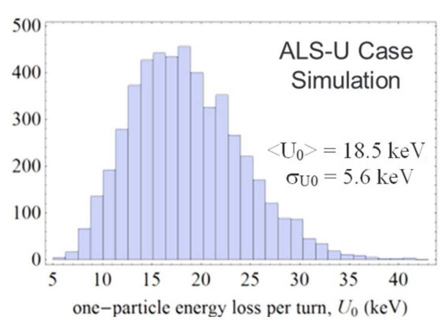

Figure 3: Expected ID-driven energy loss distribution for ALS-U user operation assuming equal probability for all ID gap positions (ALS wiggler losses not included).

The next question is: what is the level of emittance variation that we should expect during a typical user operation where ID gaps are randomly moved. Figure 3 shows the result of a simulation indicating that for the ALS-U case, we can expect an rms loss variation of about 5.6 keV. Using the information from Fig. 2 we can estimate that this would correspond to an estimated emittance variation of about 7% over a 4-sigma interval.

Such a level of variation can be tolerable for some of the user experiment techniques but as mentioned in the introduction, it can represent an issue for some others. In the next section we discuss possible emittance compensation techniques.

COMPENSATION TECHNIQUES

Emittance Compensating Wiggler

The most direct way to compensate for ID induced emittance variations is to use a variable gap wiggler (or equivalent device) dedicated to the task. The energy radiated by an electron going through a wiggler is [5]:

$$U_0 = \pi\, C_\gamma \left(\frac{m\, c^2}{e}\right)^4 \gamma^2 \left(\frac{K_w}{\lambda_w}\right)^2 L_w$$

where m and e are respectively the electron mass and charge, c the speed of light, γ the electron energy in rest mass units, K_w, L_w and λ_w are the wiggler constant, length and period respectively. C_γ is a constant with value of 8.846 x 10^{-5} m/GeV^3.

In this scheme, the gap of the compensating wiggler is closed when the other ID gaps are open, and is gradually opened when the other ID gaps are closing to keep the overall radiation losses and hence the emittance constant.

For example, the present ALS wiggler with $\lambda_w = 0.114$ m, $L_w = 3.3$ m, and a max $K_w = 20.6$ would allow to tune energy losses from a 2 GeV beam from 0 to ~ 31 keV. An advantage of this scheme is that it would allow operating at an emittance value smaller than the one obtainable from the bare lattice without IDs. The main disadvantage is that it requires a dedicated wiggler (not available to users) for the compensation process.

Compensation by Dispersion Bump in a Wiggler

The second compensation scheme we want to discuss consists of applying a horizontal dispersion η_x bump inside a wiggler with fixed gap (fixed field). We assume for the bump in the wiggler that η_x is constant and that $\eta'_x = d\eta_x/ds = 0$. In this case, the wiggler contribution to the synchrotron integrals [5] can be calculated and the related emittance variation can be estimated:

$$\Delta I_{5W} \sim \frac{4}{3\,\pi}\frac{Bw^3}{(B\rho)^3} L_w \langle\gamma_x\rangle\, \eta_x^{\,2}, \quad \Delta I_{2W} = 0, \quad \Delta I_{4W} \sim 0$$

$$\varepsilon_0 = C_q \frac{\gamma^2}{J_x}\frac{I_5}{I_2} \quad \rightarrow \quad \frac{\Delta\varepsilon}{\varepsilon} \sim \frac{\Delta I_{5W}}{I_5}$$

where $(B\rho) = p/e$, with p the beam momentum, γ_x is the Twiss parameter, $J_x = 1 - I_4/I_2$ is the horizontal partition number and C_q is a constant with value of 3.832 x 10^{-13} m. Using these formulae, the ALS wiggler parameters described in the previous section, <γ_x >= 1/2.5 m^{-1} (ALS-U 18.127) and $\eta_x = 1$ cm, we get a variation $\Delta\varepsilon/\varepsilon$ ~ 5%.

An advantage of this scheme is that it is compatible with user operation if beam size variations due to η_x in the bump are acceptable. This is true at the ALS where protein crystallographers operate the wiggler at fixed gap. Disadvantages are that the technique requires extra knobs for creating the local dispersion bump; the dispersion bump size is not negligible; and possible effects on beam dynamics need to be evaluated.

Compensation by Beam Momentum Variation

The beam momentum can be changed by varying the RF frequency. Because the synchrotron integrals depend on momentum, a change of the RF will also change the emittance. Figure 4 shows a simulation for the ALS-U v18.127 example. The results indicate that a 5% emittance variation is obtainable with ~1% momentum variation (corresponding to ~1.3 kHz RF variation).

In reality, this scheme is not practical because it moves source points in dipoles, changes the radiated photon energy, and can challenges the ring dynamic aperture.

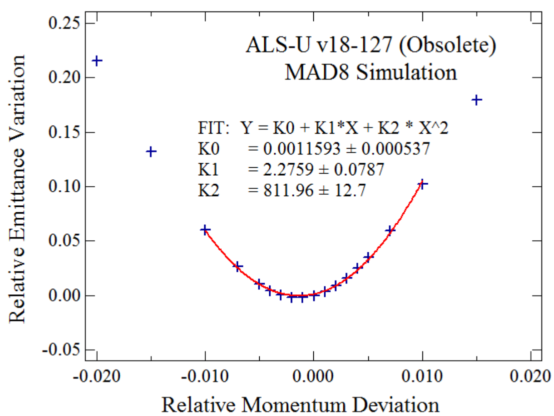

Figure 4: Simulation indicating the ALS-U v18.127 emittance dependence on the electron momentum.

Compensation Using Intra-beam Scattering

Using the Bjorken-Mtingwa formalism [6] we can evaluate the contribution of intra-beam scattering (IBS) to emittance. Such an effect is characterized by the ring transverse damping times τ_w and by the IBS time constants T_w that are proportional to the bunch length σ_z:

$$\varepsilon'_{w0} = \frac{1}{1-\tau_w/T_w}\varepsilon_{x0} \quad with \quad \frac{1}{T_w} \propto \frac{1}{\sigma_z} \qquad w = x, y$$

The last expression shows that bunch length allows for using IBS to generate the emittance variations required by the compensation scheme. This is possible in rings equipped with harmonic cavities (as in most MBA rings) where such devices can be used for varying the bunch length. Figure 5 shows the case for the ALS-U v18.127 example. IDs losses were simulated by ELEGANT by adding 12 wigglers to the ALS-U v18.127 lattice used for varying the energy losses in this study. For example, with wigglers tuned for 18 keV losses, the emittance decreases to ~95% of the no-ID value if the bunch length is not changed. To re-establish the emittance to the original value the bunch must be shortened to ~66% of the no ID value. This is a significant bunch length variation especially considering that in a Touschek dominated regime (as usually in low-energy MBAs) the beam lifetime will also reduce by the same factor.

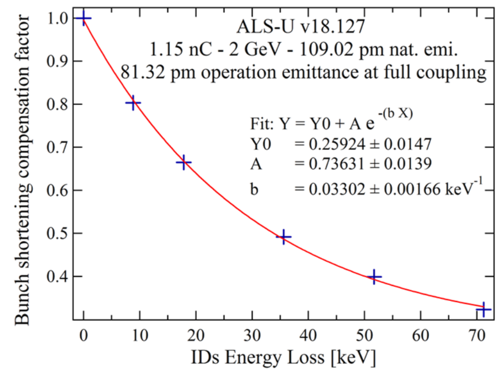

Figure 5: Simulation indicating the emittance dependence of the ALS-U v18.127 emittance on bunch length.

CONCLUSIONS

In presently proposed, being built and already built ultra-low emittance rings based on MBA lattices, radiation in the IDs represents a significant fraction of the overall energy losses. This implies that ID gaps variations during user operation can generate significant emittance variations that will ultimately translate into dynamic changes of the electron and photon beam transverse distributions. Such variations can negatively affect some of the users' experiments and should be compensated. Several compensation schemes with respective pros and cons were presented and discussed. A variable gap wiggler can maintain a constant operation emittance but it requires a dedicated wiggler. A horizontal dispersion bump in a fixed gap wiggler does not require a dedicated wiggler but requires extra knobs for the bump control, significant bump sizes, and could affect beam dynamics. Small electron beam momentum variations allow varying the emittance but move photon sources in dipoles, shift photon energy and challenge the ring dynamic aperture. Control by IBS requires significant bunch length shortening, affecting lifetime.

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