GLOBAL BETA-BEATING COMPENSATION OF THE ALS W16 WIGGLER

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Abstract

The W16 wiggler is the first wiggler and highest field insertion device to be installed in the ALS storage ring. When the gaps of the W16 wiggler are closed, the vertical tune increases by 0.065 and the vertical beta function is distorted by up to $\pm$37%. There are 48 quadrupoles in the ring whose fields can be adjusted individually to restore the tunes and partially compensate the beta-beating. In order to adjust the quadrupole field strengths to accurately compensate the focusing, it is necessary to have a method to precisely determine the beta-beating. In this paper we compare measurements of the induced beta-beating using two methods: measuring the tune dependence on quadrupole field strength and fitting a lattice model with measured response matrices. The fitted model also allows us to predict quadrupole field strengths that will best compensate the beta beating. These quadrupole field strengths are then applied and the resultant beta-beating is measured.

1 INTRODUCTION

The W16 wiggler is a high field insertion device that produces intense X-ray radiation for the study of protein crystology[1]. The wiggler has 19 periods each 16 cm in length—thus the name W16. The peak magnetic field strength, B_0, of the wiggler is dependent upon the vertical gap between the poles which can be mechanically adjusted from a maximum gap of 210 mm ($B_0 \approx 0$ T) to a minimum gap of 14 mm ($B_0 = 2$ T). For the most part, when in use, the wiggler will be set to 14 mm and when not in use and also during injection it will be set to 210 mm.

The W16 causes vertical focusing. When closed to its minimum gap of 14 mm, it is the strongest focusing insertion device in the ring. This has several deleterious effects. The first effect is that the vertical focusing increases the vertical betaton tune by 0.065, shifting the tunes relative position to the coupling resonance which causes the vertical emittance and thus the vertical beam size to change. The second effect is that the focusing produces an oscillatory distortion of the vertical beta-function that is as much as $\pm$37% of the "unperturbed" beta-function. Due to this "beta-beating", the vertical beam size changes by as much as $\pm$17% from its nominal size. The third effect is that the vertical focusing perturbs the ring's natural 12-fold symmetry causing many previously suppressed structural resonances to become excited [2]. These resonances can shorten the beam lifetime, limit the "stable" region of the the tune plane and alter the beam size and shape[2, 9].

Previous theoretical studies [3, 4, 5] have examined the effect of the wiggler and undulator focusing on the dynamics of the electron beam. The conclusion of these studies can be sumarized as follows: The focusing of the wiggler can not be locally compensated in the ALS. However, there exist 48 quadrupoles (24 QF and 24 QD) whose fields can be independently adjusted in order to partially compensate the wiggler focusing. Unfortunately, even with all these quadrupoles, it is still not possible to completely compensate all the focusing effects simultaneously. In particular one study [5] showed if the quadrupoles are adjusted to minimize the beta-beating, than the dynamic aperture shrinks. Nevertheless from an operational standpoint, compensating the beta-beating is a desirable condition if the resulting dynamic properties of the ring are acceptable.

To effectively compensate beta-beating in practice it is necessary to have a way to experimentally measure the effect of the wiggler, predict how the quadrupoles should be adjusted, and then experimentally confirm that the compensation has been achieved. In this paper we present a method for compensating the wiggler and its realization for the W16. This is also being used for Brookhaven National Laboratory's VUV ring [6, 7]. We show that the beating is reduced from $\pm$37% to less than $\pm$10% everywhere with the exception of 10 meters on either side of the wiggler. We also show that beta-beating as determined by fitting orbit response matrices is in very good agreement with measurements of the beta-beating made by varying individual quadrupole fields and measuring the change in the tune.

2 METHOD AND RESULTS

To compensate beta-beating in the ring we rely upon fitting a magnetic lattice model (COMFORT[8]) to measured orbit response matrix data using the code LOCO [6]. The orbit response matrix (sometimes called the sensitivity matrix), R, relates changes in steerer magnet currents to changes in the orbit at the beam position monitors (BPM). Parameters in the model, quadrupole gradients, BPM gains, corrector gains, and so on, are adjusted to minimize the difference, in a least squares sense, between measured orbit response matrix and one generated by the model. The general method for fitting measured response matrices is described in more detail in other papers[6, 9, 10].

2.1 wiggler gap open

Figure 1 outlines the steps we take to globally compensate the beta-beat. First the machine model is calibrated

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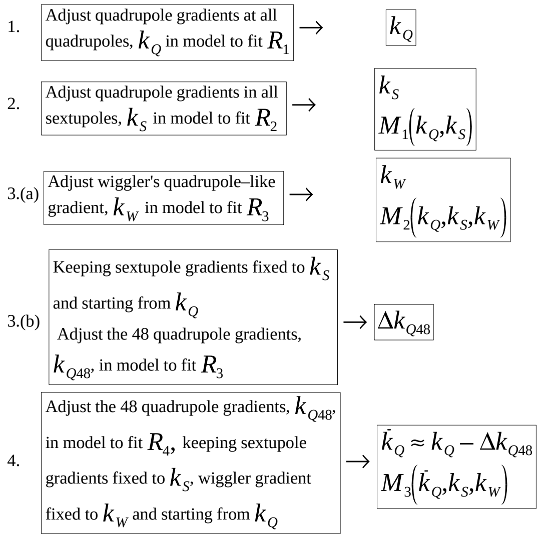

Figure 1: Steps necessary to measure and fit the beta-beating with measured orbit response matrices.

in the case where the gap is at 210 mm. This is done in two steps. The first step is to measure and fit an orbit response matrix, R_1, with the sextupole magnetic fields set to zero (step 1 in Figure 1). The matrix is fit and the individual quadrupole gradients, k_Q, are determined. The second step is to turn the sextupole magnets on and remeasure the response matrix, R_2. Sextupoles have a quadrupole gradient that is proportional to the orbit offset in the sextupole. So this second response matrix is fit by adjusting quadrupole gradients, k_S, placed at the location of the sextupoles (step 2 in Figure 1). Now a calibrated model, $M_1(k_Q, k_S)$, for the machine exists.

With this calibrated model, the beta-function can be computed at any position around the ring. The solid line in Figure 2 is a plot of relative deviation (in percent) of the vertical beta-function in the real machine from the beta-function in an ideal machine, $\Delta\beta_y/\beta_y$. As the figure indicates, the beta-beating is very small—less than $\pm$2%. (This small beta-beating is a result of earlier work with LOCO [9] where normal lattice errors were compensated.)

An independent measurement of the beta-beating is made by changing the field of the 24 QD magnets one-by-one while simultaneously measuring the change in the betatron tune. The change in tune is proportional to the change in field multiplied by the beta-function[11],

$$\Delta\nu_{yi} = \frac{\beta_{yi}}{4\pi}\Delta k_{li}, \tag{1}$$

where $\Delta\nu_{yi}$ is the change in the vertical betatron tune due to the ith QD quadrupole, β_{yi} is the vertical beta-function at the ith QD quadrupole, and Δk_{li} is the change in the ith QD quadrupole's integrated field strength. The result of this measurement is plotted as crosses (+) in Figure 2. The two beta-beating measurements agree to within a few percent.

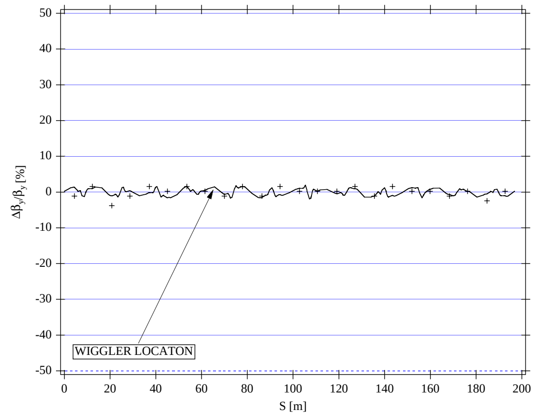

Figure 2: Relative vertical beta-beating verses longitudinal position in the case where the wiggler gap is opened.

2.2 wiggler gap closed

Next the gap of the wiggler is closed and a new orbit response matrix, R_3, is measured. This new matrix is fitted in two different ways. The first fit is to determine the induced beta-beating of the wiggler (step 3(a) in Figure 1). This is done by including a thin-lens model of the wiggler in the lattice model and adjusting its field strength, k_w, to fit R_3. The resulting beta-beating is calculated and plotted in Figure 3. As seen in Figure 3, the beating is as large as $\pm$37%. The beating has a cusp at the location of the wiggler and oscillates at twice the tune (ν_y=8.18). The tuneshift measurements are also plotted (+) and again there is good agreement.

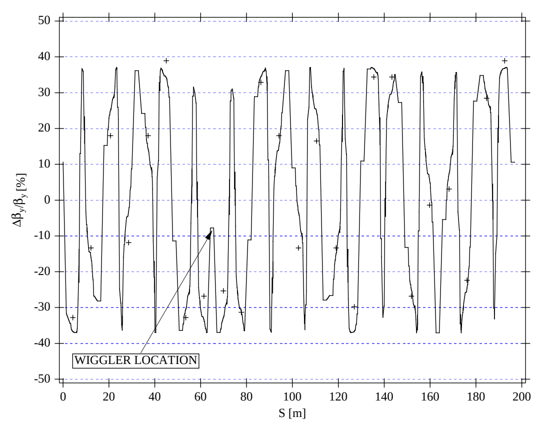

Figure 3: Relative vertical beta-beating verses longitudinal position in the case where the wiggler gap is closed.

2.3 compensation of the wiggler

Now it is necessary to determine how the quadrupoles need to be adjusted in order to best compensate the beta-beating. In particular the objective is the following: When the wiggler gap is at 14 mm and the quadrupoles are adjusted, the resulting measured orbit response matrix, R_4, should be as similar as possible to the orbit response matrix measured before the quadrupoles were adjusted and the wiggler gap is at 210 mm, R_2. This is done in the following way (step 3(b) in Figure 1). Starting from $M_1(k_q, k_s)$, LOCO fits R_3 by adjusting the gradients of the 48 quadrupoles instead of the wiggler. Now one has a new calibrated model of the ring without the wiggler where Δk_{Q48} has been added to the initial gradients,k_Q, in order to simulate the focusing effects of the wiggler. Therefore to compensate the focusing of the wiggler, one needs to subtract Δk_{Q48} from k_Q in order to best restore the matrix, R_2.

The fit resulted in quadrupole changes shown in Figure 4. There are two quadrupoles, QD7 and QD10, that have the much larger gradient changes than the others. These quadrupoles are not immediately next to the wiggler which is located between QD8 and QD9 but are the next nearest QDs.

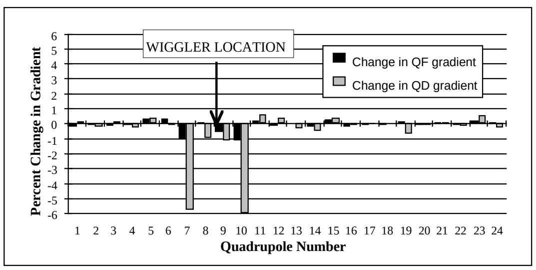

Figure 4: Experimentally determined quadrupole changes that will minimize the beta-beating generated by the wiggler $-\Delta k_{li}/k_{li}$.

The quadrupole magnets are adjusted by $-\Delta k_{li}$ and a new response matrix, R_4, is measured with the gap at 14 mm. Then R_4 is fit by adjusting the 48 quadrupoles and a new calibrated model is created (step 4 in Figure 1). The resultant beta-beating is displayed in Figure 5.

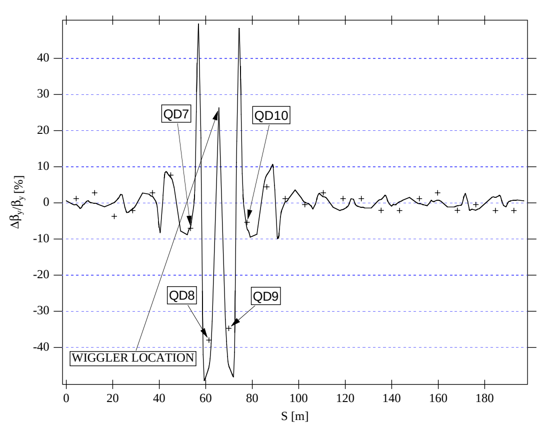

Figure 5: Relative vertical beta-beating verses longitudinal position in the case where the wiggler focusing is compensated.

From the plot one sees that the beta-beating is less that ±10%, with the exception of ±10 m on either side of the wiggler where the distortion is ±50%. In other words the beta-beating is large between QD7 and QD10 and small outside.

The reason that we are unable to eliminate the beta-beating between QD7 and QD10 has to do with the difference in phase advance between the wiggler and QD8 and QD9 which is $\Delta\phi(s) = \pm 43°$. In general, if there is a change in gradient, Δk_l, then the resultant beta-beating is [11]

$$\frac{\Delta\beta_y(s)}{\beta_y(s)} = \frac{\Delta k_l \beta_y(\bar{s})}{2\sin(2\pi\nu_y)} \cos(2\Delta\phi(s) - 2\pi\nu_y)). \qquad (2)$$

where s is the longitudinal coordinate. Because the beta-beating oscillates at $2\phi(s)$ these quadrupoles are at $2\Delta\phi(s) = \pm 86°$ away in beta-beat phase. Since the phase is so close to $2\Delta\phi(s) = \pm 90°$ from the wiggler they are orthogonal and thus virtually useless for correcting the wiggler generated beta-beat. The next quadrupoles QD7 and QD10 which have a betatron phase advance of $\Delta\phi(s) = \pm 200°$ to the wiggler are not orthogonal and can effectively correct the beta-beat.

3 CONCLUSION

We presented the results for measuring the beta-beat from the W16 wiggler. Without correction the induced beta-beating by the wiggler is as large as ±37%. With correction the beta-beat is reduced to less than ±10% everywhere except in the immediate vicinity of the wiggler. In all cases the beta-beating as determined by the calibrated model is in good agreement with the measured tuneshifts.

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