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AMPLITUDE-DEPENDENT SHIFT OF BETATRON TUNES AND ITS RELATION TO LONG-TERM CIRCUMFERENCE VARIATIONS AT NSLS-II

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Abstract

The amplitude-dependent shift of betatron tunes was measured at NSLS-II and compared with the lattice model. The comparison indicated the large change of the amplitude-tune dependence over time apparently can not be solely explained by magnets variation or beta function changes, but it seems to be explained by energy changes. On the other hand, the energy change required to fit the observed change of amplitude-tune dependence is too large to be explained by the RF frequency change and the change of the sum of orbit correctors' strengths in the period of the measurements. To explain this contradiction, our analysis shows the long-term storage ring circumference change can explain the apparent energy change. Our data indeed show a seasonal change of the amplitude-tune dependence over long-term observation. This also clearly indicated relation to the long-term closed orbit drift. Hence the current work indicates a new strategy to study how to use the amplitude-tune dependence as a guideline to analyze the long-term drift of the lattice parameters and closed orbit drift and to improve the orbit and machine performance stability.

INTRODUCTION

In 2015-2020, we systematically measured the amplitude-dependent shift of betatron tunes and compared it with the lattice model for two modes of the NSLS-II storage ring [1]: bare lattice without insertion devices and the lattice with 3 pairs of damping wigglers (3DW). To fit the data with simulation we need change setupoles and energy. Consider the possible variation range of sextupoles, the only way to explain the data is to assume a very large energy change of order of 0.5-0.7%. This appears to contradict our data records of RF frequency change, correctors strength variation, or possible beta-beat. This report points out a possible interpreation of this apparent discrepancy. We first give two examples. Due to the space limit we only compare two sets of data in Table 1,2 and leave out more data elsewhere.

The 2015 data, shown in the first 4 rows of Table 1, when compared with simulation, can be explained by an energy change of $dp = -0.4\%$ from the bare lattice mode. The measured data in 2020 in row 5-8 was very different from the data measured right after the machine commissioning in 2015. We assume the installation of 3 damping wigglers and other insertion devises during the period 2015-2020 may introduce some effective sextupoles, and even for bare lattice with the insertion devises open they remain effective.

As a model, we assume 12 effective sextupoles at the upstream ends and downstream ends of the 3 damping wigglers. The effective sextupoles are assumed to be thin sextupoles, with the same strengths as the regular sextupoles. We tried various patterns of the strengths among these 12 sextupoles by tracking simulations [2]. We simulated the effects of these sextpoles and energy change and fit with polynomials. We fit the polynomial model with the measured data, and then simulate with the fit and compare with measurements. The best fit is always for the pattern of the same strength with the same sign for all 12 effective sextupoles. We denote the strength as dK using the same scale as the regular sextupoles with 0.2 m length. The simulation gives a best agreement with the data at $dE = -1.49\%$ and $dK = -1.24\ \mathrm{m}^{-2}$ in column 3 of Table 1. Similar measured data with the lattice of damping 3 wigglers, always led to best fit with simulation assumung a large energy change during different periods. But such large energy change contradicts the RF frequency change during these periods.

Table 1: Measured Amplitude Dependence Compared With Simulation

Bare Lattice	Bare Lattice (2015) measurement	tracking by elegant using fit result by polynomials $dE = -0.4\%$
$d\nu_x/d(2J_x)$	-867	-1277
$d\nu_y/d(2J_x)$	-300	-367
$d\nu_x/d(2J_y)$	-470	-518
$d\nu_y/d(2J_y)$	-4897	-5357
Bare Lattice	**Bare Lattice (2020) measurement**	**tracking by elegant using fit result by polynomials** $dK = -1.24$, $dE = -1.49\%$
$d\nu_x/d(2J_x)$	-1317	-1134
$d\nu_y/d(2J_x)$	-19	10
$d\nu_x/d(2J_y)$	-3	-173
$d\nu_y/d(2J_y)$	-5287	-5269

Another comparison is to compare the bare lattice data and the 3DW lattice data measured in 2020 taken within one beam study shift in Table 2. The purpose is that we can check if there is an expected energy change by recording the orbit correctors' strengths and the RF frequency during the study. The measured data in column 2 for the 3DW lattice, agree with the tracking data in column 3 based on the fit $dK = -1.1$, $dE = -0.78\%$. As already shown in Table 1, the measured data in rows 5-8, column 1 for the bare lattice, agree with the tracking data in column 3 based on the fit

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Table 2: Measured Amplitude Dependence Compared With Simulation

3W Lattice	**3W Lattice measurement (Y. Hidaka 2020)**	**3W Lattice tracking using fit by polynomials** $dK = -1.1$, $dE = -0.78\%$
$d\nu_x/d(2J_x)$	-2737	-2663
$d\nu_y/d(2J_x)$	-602	-592
$d\nu_x/d(2J_y)$	-574	-734
$d\nu_y/d(2J_y)$	-4863	-5065

$dK = -1.24$, $dE = -1.49\%$. From this result it seems the main change is $dE = -0.78\% - (-1.49\%) = 0.71\%$ while dK change is very small ($dK = 0.14$). Within this study shift the beam energy change is given by $dE = \frac{1}{2\pi}\sum_i \Delta\theta_i$, where $\Delta\theta_i$ is the variation of the corrector strength. Between the bare lattice and the 3DW lattice $\sum_i \Delta\theta_i = 2.8\times10^{-5}$, so $dE = 4\times10^{-6} \approx 0$. The RF frequency change was also zero. This zero energy change contradicting the non-zero value resulted from the polynomial fit of the measured amplitude-tune dependence, is a difficulty we need to resolve.

Thus we suspect a need for a seasonal change of models to compare with. The seasonal variations of the RF frequency and of the sum strength of orbit correctors were observed in 2018-2020. A sum of the horizontal corrector currents, a sum of the vertical corrector currents, and the RF frequency are shown in the top, middle, and bottom graph of Fig. 1a), respectively. This is compared with the seasonal change of amplitude-tune dependence in Fig. 1b).

We explored another probable cause of the amplitude-tune dependency change: the remaining beta beat after lattice correction. We simulated the change of the amplitude-tune dependence using the ELEGANT code. Usually, the beta-beat is reduced to less than 1-2% after the lattice correction. The simulated change of the amplitude-tune dependence is far less than experimentally observed in the studies. The change becomes comparable to what we observed only if the beta beat is of the order of 8%. So this excluded the possibility of changes due to the beta beat.

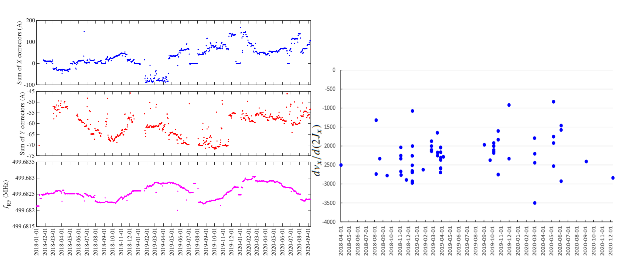

Figure 1: a) (Left) Measured seasonal variations of the RF frequency and of the sum strength of orbit correctors. b) (Right) $d\nu_x/d(2J_x)$ coefficient measured in 2018-2020.

RELATION BETWEEN THE RING CIRCUMFERENCE, ENERGY, RF FREQUENCY, CORRECTOR STRENGTH, AND GROUND MOTION

Is it possible that the RF frequency control and orbit correction between each measurement force the energy change to be zero, while the change of the amplitude-tune dependence due to the energy change remains after the orbit correction and RF control? We are going to study this possibility. We first study two conditions to see the relation between RF frequency, energy, orbit correctors, circumference, and ground motion:

Condition 1: Total Bending Angle Must Remain 2π

The first condition is that $\int d\theta = 2\pi$, where $d\theta$ is the bending angle along the ring. In the following $B(s) = B_0(s) = B_0$ in the dipole magnets, elsewhere it is zero. In addition, there are changes at discrete points of the orbit correctors δB_i, with a revision that there are Δs_j due ground or orbit motion in the dipoles, which contribute the bending angle change $\sum\limits_j \frac{\Delta s_j}{\rho_0}$, the energy change δ also contribute to the bending angle. When we neglect second order effects, since the bending angle must remain 2π, we have the change of bending angle

$$\Delta\theta = 0 = -\int \frac{B_0(s)}{B_0}\frac{ds}{\rho_0}\delta + \sum_i \frac{\delta B_i \Delta L_i \delta(s - s_i)}{B_0\rho_0}$$
$$+ \sum_i \frac{\Delta s_i}{\rho_0} = -2\pi\delta + \sum_i \Delta\theta_i + \sum_j \frac{\Delta s_j}{\rho_0},$$

where $\Delta\theta_i = \frac{\delta B_i \Delta L_i}{B_0\rho_0}$, and j is the dipole index. The sum of the corrector strength differences between the bare lattice and the 3DW lattice measured in 2020, $\sum_i \Delta\theta_i = 2.8\times10^{-5}$, $\frac{1}{2\pi}\sum_i \Delta\theta_i$ is far less than required 0.71%. Hence, $\sum_j \frac{\Delta s_j}{2\pi\rho_0}$ may account for the energy change or the amplitude-tune dependence change even if $\frac{1}{2\pi}\sum_i \Delta\theta_i = 0$, but the energy change appears to be far less than 0.7%, to be explained in the following.

Condition 2: Relation Between RF Frequency Change δf, Energy Change δ, Circumference Change ΔC, and Δs Due to the Ground Motion

Take into account the contribution of Δs to the circumference change ΔC: the condition for the relation between ΔC and the RF frequency df, the corrector strength change $\Delta\theta_i$, the relative energy change δ, and the orbit change $\Delta x(s)$:

$$\Delta C = \Delta s + \oint \frac{\Delta x(s)}{\rho} ds + \sum \Delta\theta_i D_i \delta + C\alpha_c\delta,$$

here $\oint \frac{\Delta x(s)}{\rho} ds$ is due to the orbit error, independent of δ. $\left(\int \frac{D(s)}{\rho} ds\right)\delta$ is due to δ, $\sum\limits_i \Delta\theta_i D_i \delta$ is due to the correc-

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tor strength change, Δs is due to the floor motion (thermal expansion plus the orbit change from ground motion). $\left(\int \frac{D(s)}{\rho} ds\right) \delta = C\alpha_c \delta$ is the contribution from a perfect machine (α_c is the momentum compaction). We estimate various forms of ΔC:

1. ΔC caused by thermal expansion, if a ring circumference is 800 m, and Δx is the same everywhere with 200 µm, then $R \to R + \Delta x$, and $C \to C + \Delta C = 2\pi(R + \Delta x)$, $\Delta s = \Delta C = 2\pi \Delta x = 2\pi \times 200\,\mu\text{m} = 1\,200\,\mu\text{m}$ =1.2 mm
2. ΔC caused by the energy change $\delta = 1\%$, then $\Delta s = -C\alpha_c\delta = -800$ m×3.7×10^{-4}×1% = -2960 ×10^{-6} m≈ − 3 mm
3. ΔC caused by the tranverse orbit distorsion $\oint \frac{\Delta x(s)}{\rho} ds$: since $\oint \frac{1}{\rho} ds = \Delta\theta = 2\pi$, so $\oint \frac{\Delta x(s)}{\rho} ds \sim 2\pi \Delta x \approx 6 \times 200\,\mu\text{m} \sim 1$ mm
4. ΔC caused by the corrector changes in dispersive regions $\sum D_i \delta \Delta\theta_i$, The 2020 data gives the RMS corrector strength $\sigma_\theta = 0.18$ mrad assuming random walk of 180 correctors, we get $\sqrt{180}\sigma_\theta$ =2.4 mrad, taking $D_i = 0.2$ m, even if $\delta = 1\%$, this term is neglegible.

So all estimates except $\sum D_i \delta \Delta\theta_i$ lead to ΔC of the order of 1 mm .

The estimated change of electron speed for $\delta = 1\%$ is $\frac{dv}{v} \approx 5 \times 10^{-14}$. Since $\frac{dv}{v} \ll \frac{dC}{C}$, we have $\frac{df}{f} = -\frac{dC}{C}$, i.e., if df= 0, then $\Delta C = 0$. However, if $dC = 1$ mm, then $\frac{dC}{C} = \frac{1\text{ mm}}{792\text{ m}} = 1.2 \times 10^{-6}$, the condition 2 relates dC to Δs and the closed orbit change Δx as follows:

$$\Delta C = \Delta s + \oint \frac{\Delta x(s)}{\rho} ds + \left(\int \frac{D(s)}{\rho} ds\right) \delta + \sum \Delta\theta_i D_i \delta = 0.$$

So if $\delta = 0$ and $df = 0$, then $\Delta s + \oint \frac{\Delta x(s)}{\rho} ds = 0$. This only gives a relation between $\Delta x(s)$ and Δs, and can not be used to explain the apparent change of energy. However, these estimates given above can be used to understand their relation to the amplitude-tune dependence changes over time, as follows.

EFFECT OF THE LONG-TERM CIRCUMFERENCE VARIATION ON THE AMPLITUDE-TUNE DEPENDENCE

With these two relations, and in particular, the numerical estimate of the relation between the circumference, energy change, RF frequency change, and the corrector strength change given above, we estimate the possibility of Δs effect: the change of amplitude-tune dependence behaves like it is caused by the energy change even if the energy does not change.

If there is a uniform 200 µm increase of R, all the magnets and BPMs move accordingly, then $\Delta C = 1.2$ mm, if $\delta = -0.4\%$, then closed orbit also will move accordingly and will be centered at quadrupoles, so the betatron tune will change very little. The tunes are determined by the one-turn matrix, the product of matrixes. $\Delta C/C = 1.2$ mm/792 m $\sim 10^{-6}$, so the one-turn matrix will change by the order of 10^{-6}, which is negligible. The result is the correctors' strengths also change very little, and a very little beta correction is needed. The amplitude-tune dependence will not change either. The main net effect is $\delta = -0.4\%$, but there is no other observable effect except that if we directly measure the energy we should see $\delta = -0.4\%$.

If for some reason, e.g., due to some RF tuning or RF feedback, or due to the limitation of the RF frequency tuning range, we return to $\delta = 0$, then the main result looks like $\delta = +0.4\%$. Then the amplitude-tune dependence will change like if there is $\delta = 0.4\%$. If we change the circumference by 1 mm, e.g. by increasing 1 µm for every 1 m around the ring, there will be a negligible effect observed, even by a computer. The ELEGANT tracking code specifies energy in an input file, but it does not influence the beam dynamics.

As a result, even though it is difficult to observe such a small circumference change without a complicated survey procedure, it can be observed by monitoring the amplitude-tune dependence evolution. This requires a systematic long-term study of the amplitude-tune dependence with appropriate correction of the specified machine lattices separately. In fact, our existing data indicate a seasonal pattern of the amplitude-tune dependence, as shown in Fig. 1b).

CONCLUSION

Based on the effect of circumference change mentioned above, it seems that a very small circumference change has a large effect on the energy and RF frequency, hence it affects the closed orbit and introduces the orbit distortion if the beam energy is not changed according to the circumference change based on the simple relation $\Delta s = -C\alpha_c\delta$. By changing the RF frequency according to this relation to change the energy, the dispersion pattern in the closed orbit caused by the circumference change would be reduced if the circumference change is dominated by uniform expansion or contraction. The adjustment of the energy change according to the circumference change may be carried out based on the guidance of the amplitude tune-dependence variation and its correction.

Whether this can improve the long-term orbit stability would still depend on the experimental test to confirm. Hence we suggest a systematic study of this possibility. If it is indeed such a case, there might be an improvement in the beamline alignment for synchrotron light sources. Obviously, this implies a significant change of closed orbit correction and RF frequency adjustment procedure of the storage ring.

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