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FIRST DEMONSTRATION OF THE TRANSPARENT FAST-TO-SLOW CORRECTOR CURRENT SHIFT IN THE NSLS-II STORAGE RING*

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Abstract

To realize the full benefits of the high brightness and ultra-small beam sizes of NSLS-II, it is essential that the photon beams are exceedingly stable (≤ 10% beam size). In the circumstances of implementing local bumps, changing ID gaps, and long term drifting, the fast orbit feedback (FOFB) requires shifting the fast corrector strengths to the slow correctors to prevent the fast corrector saturation and to make the beam orbit stable in the sub-micron level. As the result, a reliable and precise technique of fast-to-slow corrector strength shift has been developed and tested at NSLS-II. This technique is based on the fast corrector response to the slow corrector change when the FOFB is on. In this article, the shift technique is described and the result of proof-of-principle experiment carried out at NSLS-II is presented. The maximum fast corrector current was reduced from greater than 0.45 A to less than 0.04 A with the orbit perturbation within ±1 µm. Especially when the step size of the shift was below 0.012 A, the amount of noise being added to the beam was none.

INTRODUCTION

NSLS-II is a third generation 3GeV electron storage ring (SR) with ultra-low emittance [1]. In order to fully benefit from the high brightness and small beam sizes, it is essential that the photon beams are exceedingly stable, assuring constant intensity after apertures, constant photon energy after monochromators, and minimal photon source size and highly precise steering accuracy for focusing on small samples. The FOFB design is based on the common case of 1:1 focusing optics, the position stability of the photon beam on the sample is directly related to that of the electron beam. The position of the photon beam should be stable to a level of Δ_y/σ_y ~10%. It requires the electron beam motion of no more than 10% of the beam size, particularly in the frequency range from ~10 mHz to 250 Hz [2, 3]. This tolerance has been adopted by many synchrotron radiation laboratories. Since the minimum vertical beta function is about 1 m (Fig. 1 for a super-period), when we take the diffraction-limited vertical emittance ($\lambda/4\pi$) for 1 Å photons, the vertical beam size is 2.7 µm RMS. Therefore, the beam position stability should be ~0.3 µm in the short straight section.

For the NSLS-II closed orbit feedback system, in order to limit the noise caused by digital step changes of the power supplies in the FOFB system, the angular kick corresponding to the last bit of the power supplies for the fast correctors must be smaller than 3 nrad [2]. On the other hand, to carry out closed orbit alignment or orbit correction after a long term drift, strong correctors with 0.8 mrad kick strength are needed [1]. In order to avoid the requirement of correctors with both large strength and very small minimum step size, two separate sets of slow correctors with large strength and fast correctors with smaller maximum strength are installed in NSLS-II.

Since the NSLS-II commissioning, there are several occasions when users were implementing local bumps and changing ID gaps, etc., the fast correctors were driven into saturations and the beam orbit stability suffered. Therefore, a reliable and robust technique of transferring the DC components of the fast correctors to slow correctors becomes essential for the successful operation of NSLS-II.

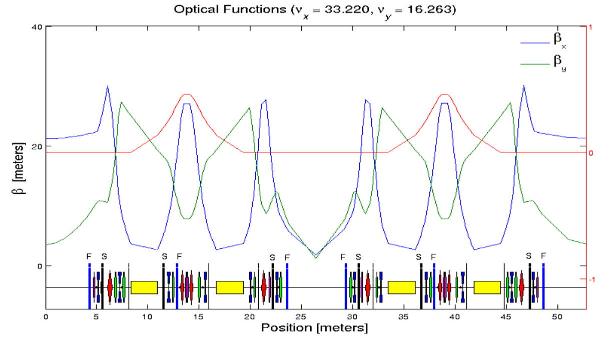

Figure 1: Beta functions and dispersion (top) and machine elements (bottom) in a super-period. In the bottom, positions of fast correctors and slow correctors are indicated by vertical blue lines with label ‘F’ and vertical black lines with label ‘S’ respectively.

DESCRIPTION OF THE METHOD

In NSLS-II, 90 horizontal and 90 vertical fast correctors have been installed for the FOFB system. The maximal kick angle of a fast corrector is 0.015 mrad, it is limited by the power supply maximal current of 1.2 A. For a reliable operation of the FOFB system, the current of every fast corrector must be well below the 1.2 A limit.

In order to avoid fast and slow feedback systems working in parallel, and avoid the possible interaction between two feedback systems, only the FOFB system is running during operation to guarantee the full benefit of the high precision (sub-nrad step size) power supplies of the FOFB system. However, several occasions when the fast correctors being driven into saturation are observed: long-term drift; implementing local bumps; changing ID gaps; orbit correction. Therefore, the FOFB system requires the slow correctors periodically removing the DC components of the fast correctors such that the DC components in the FOFB system do not accumulate to reach saturation even

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after a large long term drift of the closed orbit motion. Meanwhile, the beam orbit is required to be stabilized in the sub-micron level all the time in the top-off operation.

The 180 slow orbit correctors are installed in the SR. The maximum kick angle of a slow corrector is more than fifty times larger than that of a fast corrector. NSLS-II storage ring is purposely designed in such a way that there always exists a slow corrector, which is next to each fast corrector with a phase advance less than a few degrees [2], as shown in Fig. 1. Those paired fast and slow correctors perform similarly in correcting the orbit perturbation. As the result, it enables the smooth transfer of the fast-to-slow corrector strengths while maintaining the stable beam orbit. There exist other approaches, as an example, APS unifies operation of both slow and fast correctors in a single feedback algorithm [4].

We choose the 90 slow correctors, which are paired with the 90 fast correctors in both horizontal and vertical planes, to perform the shift. The advantage of choosing the paired fast and slow correctors is that there always exists a unique solution, which guarantees convergence. One can also choose all 180 slow correctors; however, the solution must be carefully constrained to avoid the cross-talk between different slow correctors [5].

NSLS-II SR machine lattice has been well corrected to the design lattice. Therefore, we have a well-represented lattice model of the NSLS-II SR [6]. Using this model, we can simulate the entire fast-to-slow corrector shift process in the Matlab Middle Layer (MML) using Accelerator Toolbox (AT) package [7].

The procedure, which is applicable to horizontal (X) and vertical (Y) planes separately, is described as the following:

1. Obtain the difference orbit ΔX *via* varying one of the 90 slow correctors paired with the fast correctors in bipolar mode by ±0.5 A.
2. Correct the difference orbit ΔX using all 90 fast correctors and the model orbit response matrix (ORM). The result of the fast corrector current changes becomes a column of the slow-to-fast corrector-shift matrix $\mathbf{M}_{s\to f}$.
3. Repeat steps 1 and 2 for all 90 paired slow correctors to obtain the full slow-to-fast corrector-shift matrix $\mathbf{M}_{s\to f}$ with the dimension of 90×90.
4. Invert the square matrix $\mathbf{M}_{s\to f}$ to obtain the fast-to-slow corrector-shift matrix $\mathbf{M}_{s\to f}{}^{-1}$.
5. Repeat steps 1 to 4 for the Y plane.

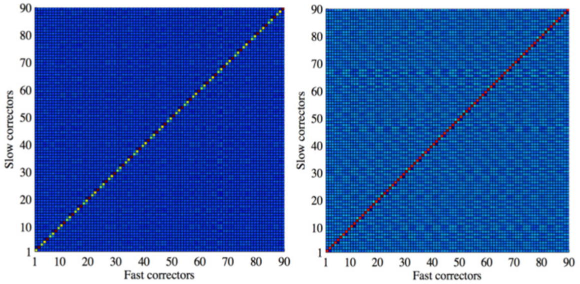

Figure 2: Modeled fast-to-slow corrector-shift matrices: horizontal (left) and vertical (right).

Figure 2 shows the horizontal and vertical matrices $\mathbf{M}_{s\to f}{}^{-1}$ calculated *via* AT using the lattice model of NSLS-II SR. As one can see, both matrices are diagonally dominant because every fast corrector has a paired slow corrector, which is the most effective one to compensate the orbit perturbation caused by this fast corrector. Thus the vector of additional currents $\Delta\mathbf{I}_s$ of these 90 slow correctors required for compensation of the fast corrector currents $\mathbf{I}_f$ is: $\Delta\mathbf{I}_s = \mathbf{M}_{s\to f}{}^{-1}\mathbf{I}_f$. Ideally, the orbit should not be perturbed if we change the settings of the slow correctors by $\Delta\mathbf{I}_s$ and set all fast correctors to zero in a synchronous way. Practically, applying the correction iteratively is more robust and reliable.

We should study how to practically implement this fast-to-slow corrector-shift process because it should be carried out sufficiently slow for the following reasons:

1. The shift function only aims to transfer the DC values of the fast correctors to the slow correctors. Since the fast beam motion is mostly reduced by the FOFB system, the fast corrector strengths can vary rapidly. If we do not average the readings from the fast correctors over sufficiently long time, the high frequency components in the fast corrector strengths are shifted into the slow correctors and will generate unnecessary disturbances in the orbit. Hence the fast corrector read-back has to be averaged in seconds or even longer time level. The time required for the averaging should be determined experimentally, so that the RMS variation of the fast corrector readings should generate much less than the tolerated beam motion. So it should be much less than 1 µrad or may be about 0.2 µrad, depending on whether the time required is acceptable.
2. The amount of the shift in each step must be small, such as the last digit of a corrector setting, to keep the orbit motion below sub-micron level during the transfer process. When the steps are sufficiently small and taken slowly, the orbit motion caused by these changes is suppressed by the fast orbit feedback and the motion caused by the shift process should be below the noise level.
3. The number of steps in each shift can be determined by steps 1 and 2. They must be completed before the next measurement starts.
4. For the role of avoiding saturation due to long-term drift, the shift function should be turned on all the time when FOFB loop is closed.
5. The fast-to-slow corrector-shift matrix is largely independent of the FOFB settings such as the proportional–integral–derivative controller (PID) coefficients k_p, and k_i because the shift matrix is determined by the system response at very low frequency (close to the DC level). But if the linear lattice is modified significantly, the matrix $\mathbf{M}_{s\to f}$ should be re-measured or re-modeled based on the live machine lattice.

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EXPERIMENTAL RESULTS

We performed a beam-based test of the fast-to-slow corrector-shift procedure in the horizontal plane. The beam current was 25 mA. At the beginning of the experiment, the maximum fast corrector current was about 0.45 A and the FOFB system was on. We carried out the following steps:

1) Measure the fast corrector currents $\mathbf{I}_f$ once by averaging the read-back in 0.1 s.
2) Calculate the slow corrector currents $\Delta\mathbf{I}_s = \mathbf{M}_{s\to f}{}^{-1}\mathbf{I}_f$ needed to reduce the fast corrector currents $\mathbf{I}_f$ to zero and apply only 10% of the required change $\Delta\mathbf{I}_s$.
3) Wait 5 seconds and repeat steps 1) and 2).

We were able to successfully reduce the sum of absolute current of all horizontal fast correctors from 2.3 A to 0.45 A in about 4 minutes and the maximum fast corrector current from 0.45 A to 0.04 A. Figure 3 shows the evolution of the sum of absolute current of all horizontal fast correctors in comparison with the sum of absolute current change of all horizontal slow correctors during the shift period.

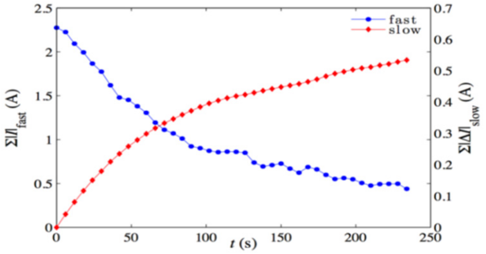

Figure 3: Sum current of all horizontal fast correctors (blue) and sum current of all horizontal slow correctors (red). The total time is about 4 min.

At the same time, the orbit was measured by 120 BPMs located at zero dispersion (to exclude orbit perturbations caused by longitudinal motion). As shown in Fig. 4(a), the horizontal orbit deviation was kept well below 1 μm level, except two BPMs with +1.1 μm and -1.3 μm offsets. The data plotted in Fig. 4(a) was averaged over 0.1 s. Besides, in order to know how much noise being added to the beam during the shift, we were continuously saving the data, which covers the entire shift starting from the maximum fast corrector current 0.45 A down to 0.04 A, at the sampling frequency of 10 kHz. As shown in Fig. 4(b), integrated PSDs at two different maximum fast corrector currents, 0.41 A and 0.12 A, were plotted as red and green curves respectively. The integrated PSD without shift was plotted as reference in blue. Obviously when the step size of the shift was below 0.012 A, which is10% of the maximum fast corrector current, the amount of noise being added to the beam was negligible. Furthermore, the maximum orbit deviations in two different cases, the one covering the shift period starting from the maximum fast corrector currents 0.12 A (red curve) and the other being taken in a similar time period without shift (blue curve), were plotted in Fig. 5. They are similar enough to evidence a transparent shift. Here, 10 s data was chosen for the integrated PSD analysis to guarantee each data set covering at least one shift due to a 5 s waiting time between two consecutive shifts. For confirmation, we repeated the experiment several times, and the results were similar.

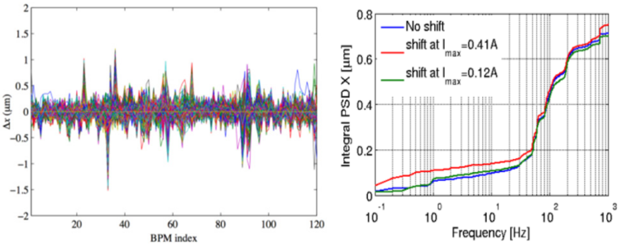

Figure 4: (a) (Left) The horizontal orbit deviation measured by 120 non-dispersive BPMs during the shift process. (b): (Right) Integrated PSDs at three different cases, without shift (blue), with shift at the maximum fast corrector current of 0.41 A (red), and with shift at the maximum fast corrector current of 0.12 A (green).

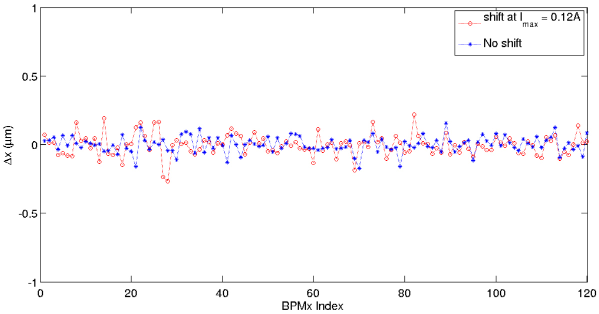

Figure 5: Maximum orbit deviations at two different cases, without shift (blue) and with shift at the maximum fast corrector current of 0.12 A (red).

We carried out a similar experiment in the vertical direction. We were able to reduce the sum of absolute current of all fast correctors from 2.3 A to 0.31 A in about 4 minutes and the maximum fast corrector current from 0.53 A to 0.016 A.

At the same time, the vertical orbit was measured by all 179 BPMs (excluding the bad BPM #102). The orbit deviation was kept well below 1 μm level. The integrated PSD indicates when the step size of the shift was below 0.013 A, the amount of noise being added to the beam was negligible; besides, the maximum orbit deviations evidence a transparent shift. We repeated the experiment several times and got similar results.

CONCLUSION

To avoid fast corrector saturation degrading the FOFB performance, we have implemented and successfuly tested the method of real-time redistributing the fast corrector strengths to the paired slow correctors with the closed loop of FOFB. The fast-to-slow corrector-shift matrix has been calculated *via* AT using the machine model of NSLS-II SR. We are able to successfully reduce the maximum fast corrector current from 0.45 A to 0.04 A with the orbit perturbation within ±1 μm. When the step size of the transferring is sufficiently small, the shift is demonstrated to be completely transparent to the beamline users. The result is repeatable. Therefore, the method is robust and ready for applying to the daily operation of NSLS-II.

In the future, we will study the performance improvement by optimizing the parameters of the fast-to-slow shifting algorithm, such as the time of averaging the fast corrector read-back and the step size of applying the correction.

ACKNOWLEDGMENTS

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