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Experimentally demonstrating the current shifting between fast and slow correctors in NSLS-II SR when the FOFB on

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TITLE

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Abstract

In the following, we describe a method of shifting strengths of fast correctors to slow correctors, while the fast orbit feedback (FOFB) is turned on. This method has been developed to prevent saturation of the fast correctors, which results in degradation of the FOFB performance. At NSLS-II, we experimentally demonstrated a successful fast-to-slow corrector strength transfer. The maximal fast corrector current has been reduced from greater than 0.45 A to less than 0.04 A. At the same time, the beam orbit was stabilized within ±1 μm level, which is acceptable by the operational standard. Now, the method is ready for release to the routine operations.

Description of the Method

NSLS-II FOFB system is designed to keep the beam orbit stability less than 10% of beam size, which is at the sub-micron level in the center of the short straights [1]. 90 horizontal and 90 vertical fast correctors have been installed in NSLS-II storage ring (SR) for the FOFB. 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 reliable operation of the FOFB system, the current of every fast corrector must be well below the 1.2 A limit.

There are several reasons of moving fast correctors to saturation:

- long-term drift,
- implementing local bumps,
- changing ID gaps,
- orbit correction.

Therefore, the FOFB system requires shifting fast corrector strengths to slow correctors to prevent the fast corrector saturation during the above-listed processes and make the beam orbit stable in the sub-micron level all the time.

180 slow orbit correctors are installed in the storage ring. 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 the phase advance less than a few degrees. Those paired (fast and slow) correctors perform similarly in correcting the orbit perturbation. As the result, it enables the smooth transfer of fast-to-slow corrector strengths while maintaining the stable beam orbit.

We choose 90 slows correctors, which are paired with 90 fast correctors in both horizontal and vertical plane, to perform the shift. The advantage of choosing the paired fast and slow correctors is that there always exists a unique solution, which guarantees the convergence. One can also choose all 180 slow correctors; however, the solution must be carefully constrained to avoid the fighting between different slow correctors [2].

NSLS-II SR machine lattice has been well corrected to the design lattice. Therefore, we have a well-represented lattice model of NSLS-II SR [3]. Using the model, we can simulate the entire fast-to-slow corrector shifting process in the Matlab Middle Layer (MML) using Accelerator Toolbox (AT) package [4].

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

1. Varying one of the 90 slow correctors paired with the fast correctors in bipolar mode ±0.5 A, find the difference orbit ΔX.
2. Correction of the difference orbit ΔX using all 90 fast correctors and the model orbit response matrix (ORM). The resulting vector of the fast corrector currents is one column of the slow-to-fast corrector-shifting matrix $\mathbf{M}_{s\to f}$.
3. Repeating steps 1 and 2 for all those 90 slow correctors to obtain the full slow-to-fast corrector-shifting matrix $\mathbf{M}_{s\to f}$ with dimensions 90×90.
4. Invert the square matrix $\mathbf{M}_{s\to f}$ to obtain the fast-to-slow corrector-shifting matrix ${\mathbf{M}_{s\to f}}^{-1}$.
5. Repeat steps 1 to 4 for the *Y* plane.

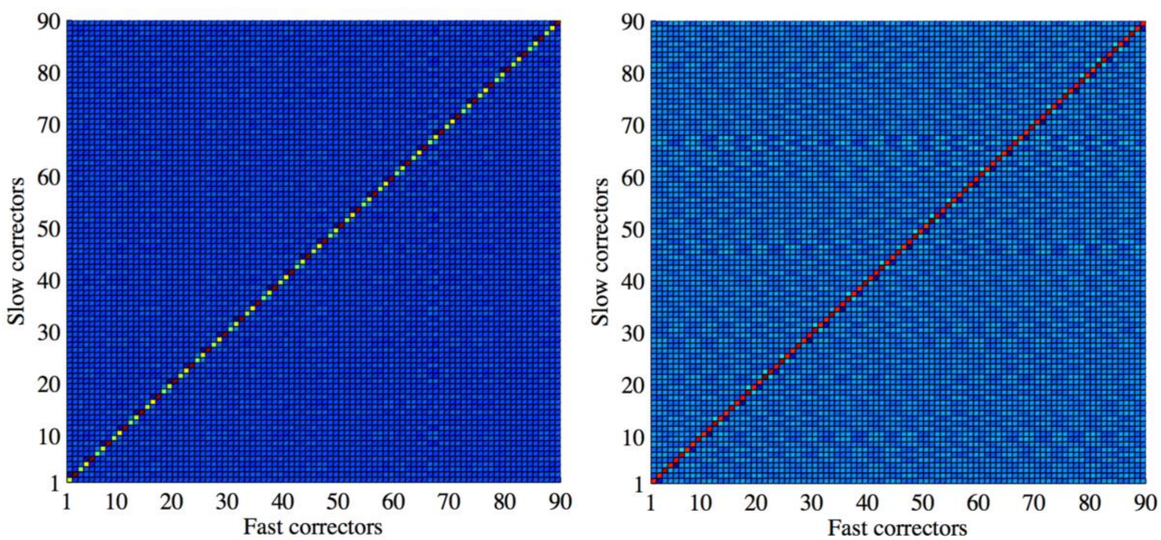

Fig. 1. Modeled fast-to-slow corrector-shifting matrices: horizontal (left) and vertical (right).

Fig. 1 shows the horizontal and vertical matrices ${\mathbf{M}_{s\to f}}^{-1}$ calculated using the AT 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 to zero all the fast correctors. Practically, the iterative application is more robust and reliable.

We should study how to implement this fast-to-slow corrector-shifting procedure because they should be carried out sufficient slowly for the following reasons.

1. The shifting function only aims to transfer the low frequency (sub-Hertz) values of the fast correctors to the slow correctors. The fast beam motion should be handled by the fast feedback system. Because the fast beam motion is mostly reduced by the fast correctors, the fast corrector strengths change 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 microradian or may be about 0.2 microradian, depends on whether the time required is acceptable.
2. The amount of the shifting 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 shifting process should be below the noise level.
3. The number of steps in each shifting 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 shifting function should be turned on all the time when FOFB loop is closed.
5. The fast-to-slow corrector-shifting matrix is largely independent on the FOFB setting such as the PID coefficients k_p, and k_i because the shifting matrix is determined by the system response at very low frequency (such as at DC level). But if the linear lattice is modified significantly, the matrix $\mathbf{M}_{s\to f}$ should be re-measured or re-modeled.

Experiment and Results

We performed a beam-based test of the fast-to-slow corrector-shifting procedure applied to the horizontal fast correctors of NSLS-II storage ring. The beam current was 25 mA. At the beginning, the maximum fast corrector current was about 0.45 A; the FOFB system was on. We carried out the following steps:

1) Measure the fast corrector currents $\mathbf{I}_f$ once.

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 current of all horizontal fast correctors from 2.3 A to 0.45 A in about 4 minutes; the maximum fast corrector current was decreased from 0.45 A to 0.04 A. Fig. 2 shows the evolution of a sum current of all fast correctors in comparison with a sum current of all slow correctors during the shifting period.

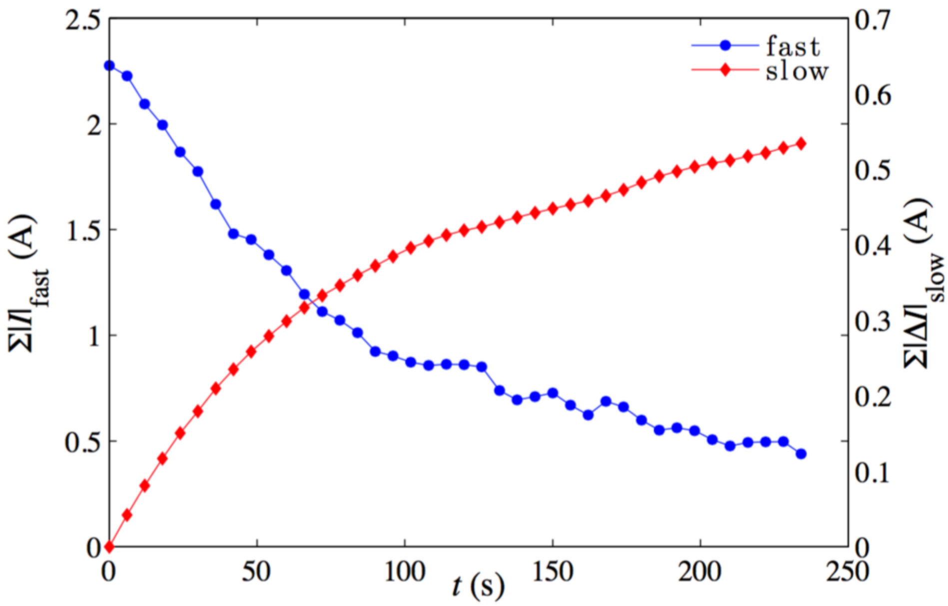

Fig. 2. Sum current of all horizontal fast correctors (blue) and sum current of all horizontal slow correctors (red). The total time is about 4 min.

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. 3, the horizontal orbit deviation was kept well below 1 µm level, except two BPMs with +1.1 µm and -1.3 µm offsets. For confirmation, we repeated the experiment several times, and the results were similar.

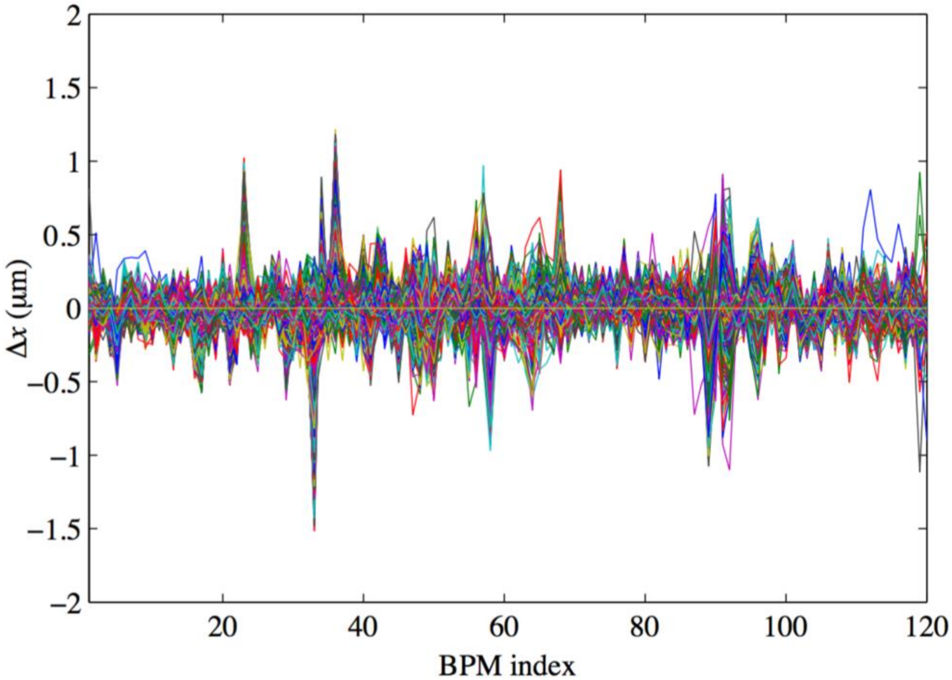

Fig. 3 The horizontal orbit deviation measured by 120 non-dispersive BPMs during the shifting process.

Similarly in the vertical direction, we were able to reduce the sum current of all fast correctors from 2.3 A to 0.31 A in about 4 minutes; the maximum fast corrector current was decreased from 0.53 A to 0.016 A. Fig. 4 shows the evolution of a sum current of all fast correctors in comparison with a sum current of all slow correctors during the shifting period.

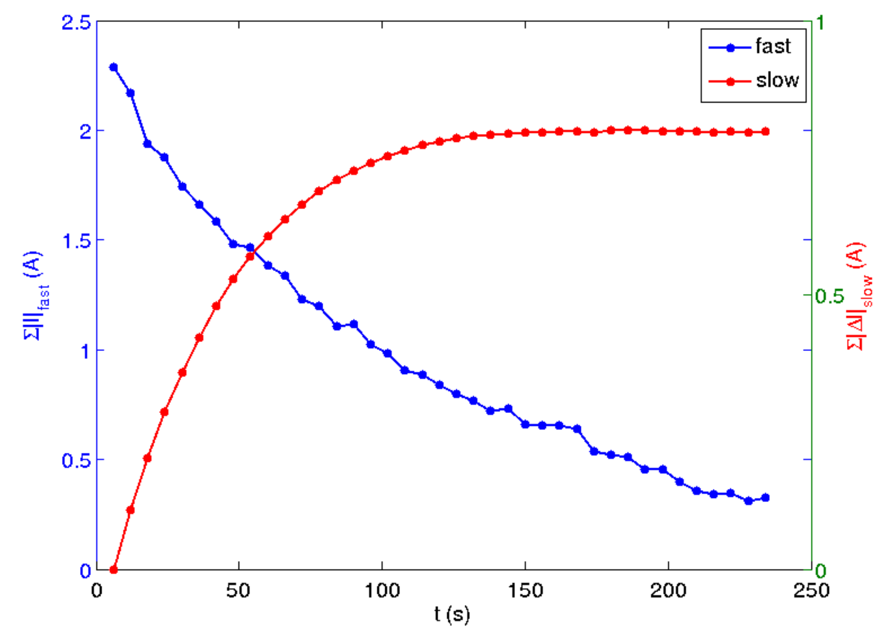

Fig. 4. Sum current of all vertical fast correctors (blue) and sum current of all vertical slow correctors (red). The total time is about 4 min.

At the same time, the vertical orbit was measured by all 179 BPMs (excluding the bad BPM #102). As shown in Fig. 5, the orbit deviation was kept well below 1 μm level, except several BPMs with +1.3 μm and -1.3 μm offsets. Also, we repeated the experiment several times, and the results were similar.

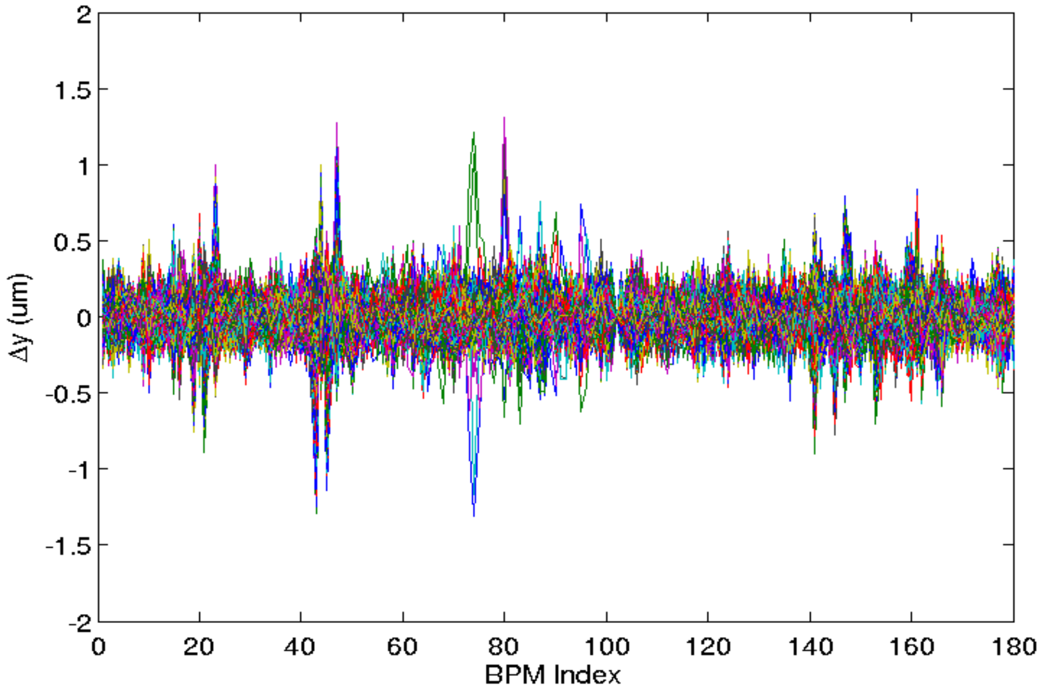

Fig. 5 The vertical orbit deviation measured by all 179 good BPMs during the shifting process.

Conclusion

We have developed and tested a method of real-time redistribution of correction strength from fast correctors to slow correctors, with closed loop of fast orbit feedback. The fast-to-slow corrector-shifting matrix has been calculated using the AT lattice model of NSLS-II storage ring. 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 level. The result is repeatable; therefore, the method is robust and ready to releasing for the operation. In the future, we should explore the further improvement by averaging the fast corrector read-back with a longer time other than 0.1 second and also by applying a smaller-step correction with less orbit disturbance.

References

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