BNL-211194-2019-TECH

NSLSII-ASD-TN-248

NSLS-II Storage Ring BPM Calibration via LOCO

X. Yang,

April 2017

Photon Sciences

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC), Basic Energy Sciences (BES) (SC-22)

DISCLAIMER

NSLS II TECHNICAL NOTE BROOKHAVEN NATIONAL LABORATORY	NUMBER **NSLSII-ASD-TN-248**
AUTHOR **X. Yang**	DATE **04/10/2017**
TITLE **NSLS-II Storage Ring BPM Calibration *via* LOCO**	

NSLS-II Storage Ring BPM Calibration *via* LOCO

Xi Yang

April 10, 2017

Abstract

In the following, we describe a method of the beam based calibration of the beam position monitor (BPM) system in the NSLS-II storage ring (SR) *via* the LOCO (Linear Optics from Closed Orbits) technique [1,2]. This method measures the orbit response matrix (ORM) and the dispersion function of the machine. The data are then fitted to a lattice model by adjusting parameters such as quadrupole and skew quadrupole strengths in the model, BPM gains and rolls, corrector gains and rolls of the measurement system. Therefore, BPM gains and rolls are obtained.

Introduction

There is an option in the LOCO analysis to compute the BPM and corrector magnet gain and coupling corrections. Basically the BPM corrections are applied to the model response matrix to best match the measurement using the following equation.

$$\begin{pmatrix} x_{meas} \\ y_{meas} \end{pmatrix} = \begin{bmatrix} G_x & G_{xy} \\ G_{yx} & G_y \end{bmatrix} \begin{pmatrix} x_{model} \\ y_{model} \end{pmatrix} \qquad (1)$$

G_x, G_y, G_{xy}, and G_{yx} are the BPM_x gain, BPM_y gain, BPM_x coupling, and BPM_y coupling respectively.

The purpose of this note is to document how the BPM system in the NSLS-II SR has been calibrated *via* the LOCO technique since the commissioning. It includes sections of BPM calibration *via* DC LOCO, BPM calibration *via* AC LOCO [3], numerical investigation of the BPM calibration precision, overcome degeneracy, avoid fitting parameter cross-talks, comparision of DC and AC LOCO results, procedure for BPM calibrations, and conclusion.

BPM Calibration via DC LOCO

It takes an hour for a complete set of LOCO measurement in the NSLS-II SR when all 360 (180 per plane) orbit correctors are used. Therefore, LOCO suffers from systematic errors caused by slow drifts of machine parameters during the measurement, as well as by hysteresis effects of adiabatic (DC) variations of slow corrector magnets.

- ***Corrector choices***

For the purpose of speeding up the ORM measurement without degrading the BPM calibration precision, we perform the following study to determine the minimum number of correctors. We use all 360 correctors for the ORM measurement; afterwards, we vary the number of the correctors used in the LOCO analysis and compare the BPM calibration results:

Index of the corrector choice in figure 1:

#***1***: 180 correctors

#***2, 3, 4, 5***: 4 sets of different choices of 90 correctors

#6, 7, 8, 9, 10: 5 sets of different choices of 60 correctors

#***11, 12, 13, 14, 15, 16***: 6 sets of different choices of 30 correctors

#***17, 18, ..., 24***: 8 sets of different choices of 15 correctors

The criteria for a good corrector choice is: *chi2* reduction, which is the ratio of *chi2* in the last LOCO iteration and in the 0^{th} iteration, is minimized (most important); standard deviations (*STD*) of BPM calibrations in x and y dimensions are small and close to the values when all correctors are used in the analysis; the maximum and minimum BPM gains are close to one; the measurement time, which is proportional to the number of correctors being used, is minimized. As shown in figure 1, it is clear that the best choice is the 60 corrector case with the index #15. Since then, this configuration has been used in the LOCO measurement. It takes about 20 minutes for a complete set of the LOCO measurement.

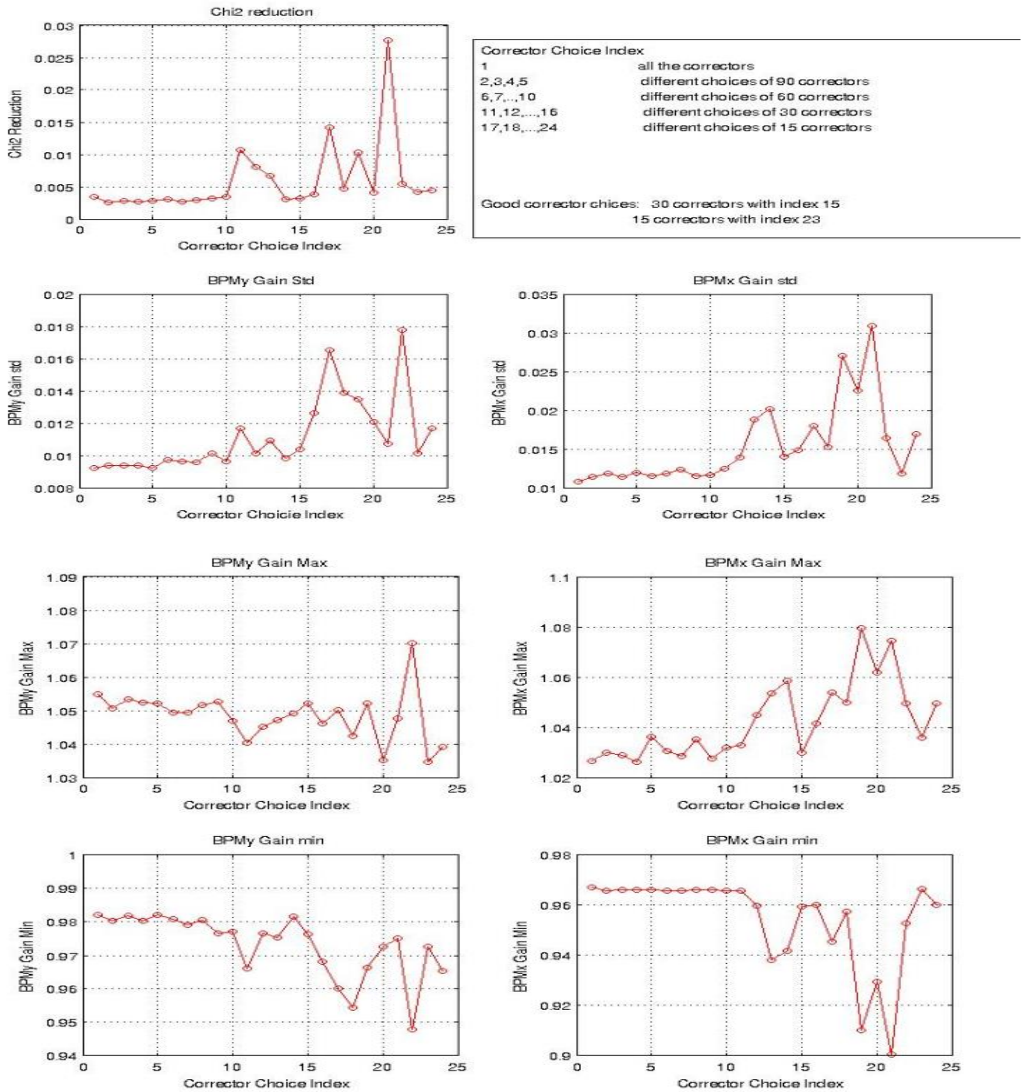

Fig. 1. LOCO analysis results: *chi2* reduction, STD of the BPM gains, the maximum and minimum BPM gains at various corrector choices in the LOCO analysis.

- ***BPM calibrations***

There are 13 different sets of DC LOCO measurements, which were made in the period of December 2014 to September 2015. Here, DC LOCO means the standard LOCO technique [1]. Figure 2 shows the BPM_x (top) and BPM_y (bottom) gains respectively. Figure 3 shows the BPM_x (top) and BPM_y (bottom) couplings.

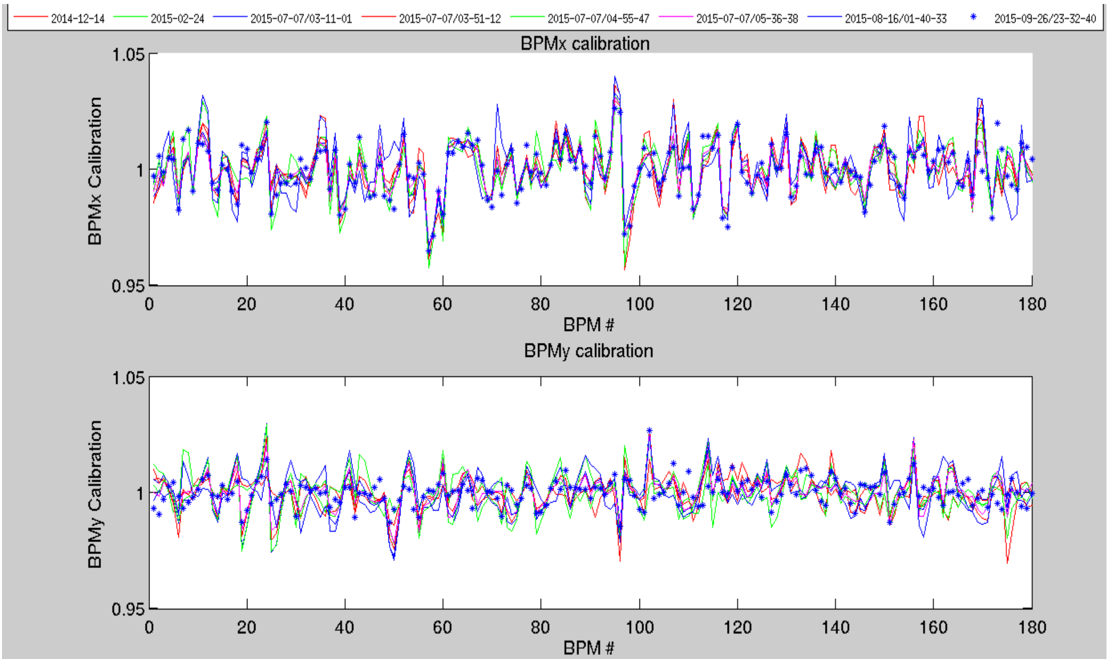

Fig. 2. Measured BPM gains *via* the LOCO method: horizontal (top) and vertical (bottom).

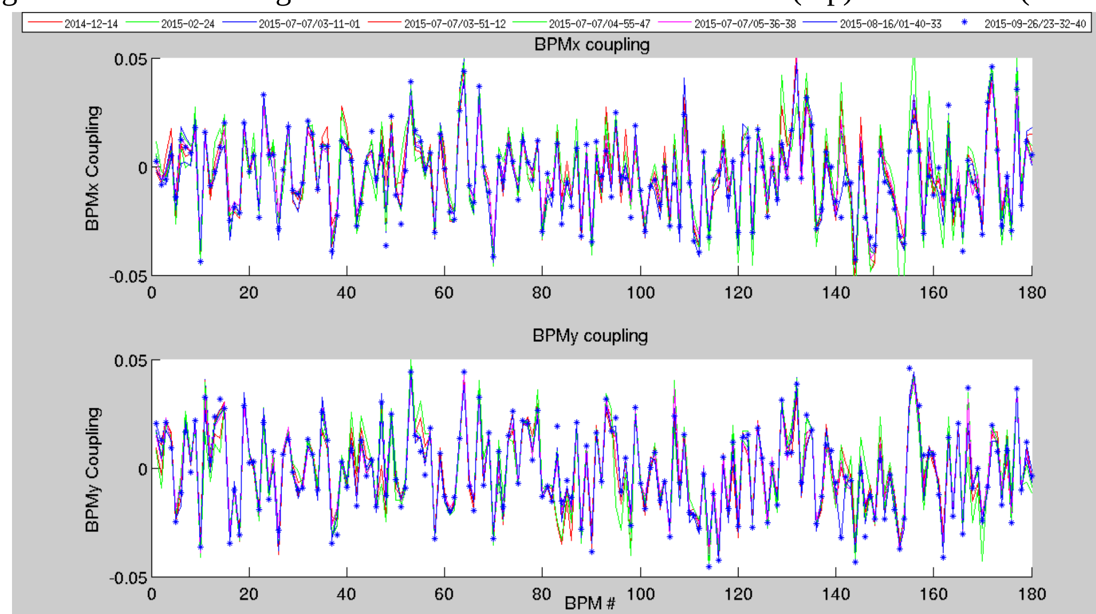

Fig. 3. Measured BPM couplings: horizontal (top) and vertical (bottom).

BPM gain errors are estimated *via* the RMS deviation of the BPM gain from those 13 sets of LOCO data. Figure 4 shows the BPM_x (top) and BPM_y (bottom) gain errors. The average gain errors over all 180 BPM_x and 180 BPM_y are 0.4% and 0.45% respectively.

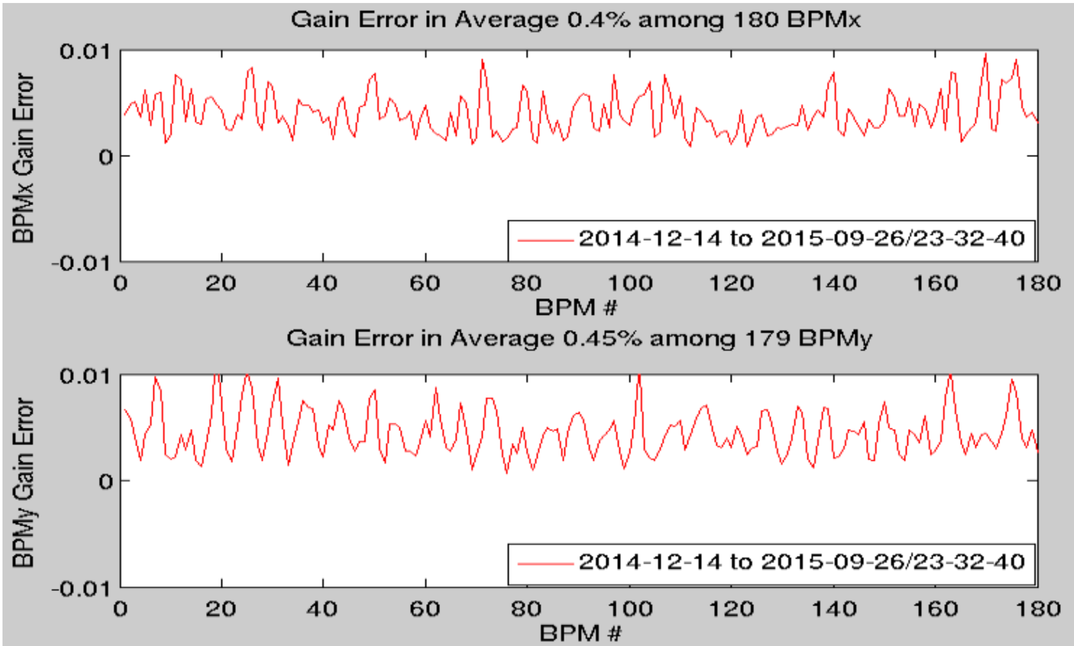

Fig. 4. Measured BPM gain errors in the period of December 2014 to September 2015: horizontal (top) and vertical (bottom).

BPM Calibration via AC LOCO

A new AC LOCO technique of magnet lattice correction has been developed and experimentally demonstrated at NSLS-II [3]. AC LOCO is based on the ORM measurement with a sine-wave excitation of the beam using fast correctors. Compared to the standard LOCO, which has a measurement precision of 1 µm, AC LOCO successfully achieves 15-nm precision. The significantly improved accuracy of the ORM measurement could potentially improve the precision of the BPM calibration.

Figure 5 shows the BPM_x (top) and BPM_y (bottom) gains respectively *via* AC LOCO. Figure 6 shows the BPM_x (top) and BPM_y (bottom) couplings.

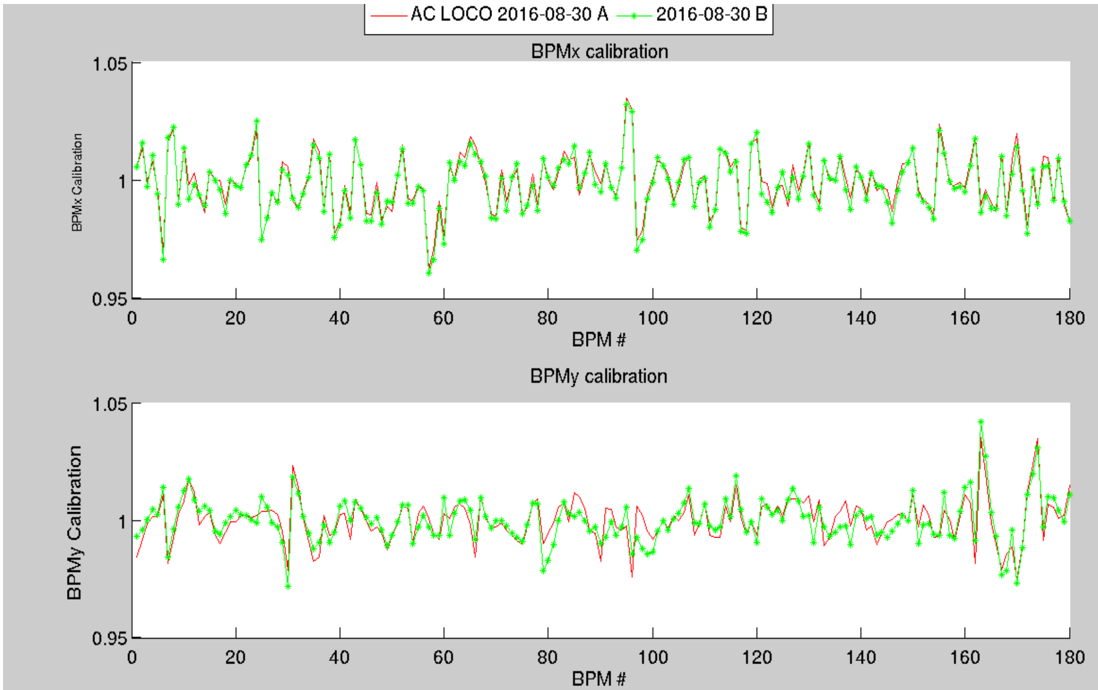

Fig. 5. Measured BPM gains *via* AC LOCO technique: horizontal (top) and vertical (bottom).

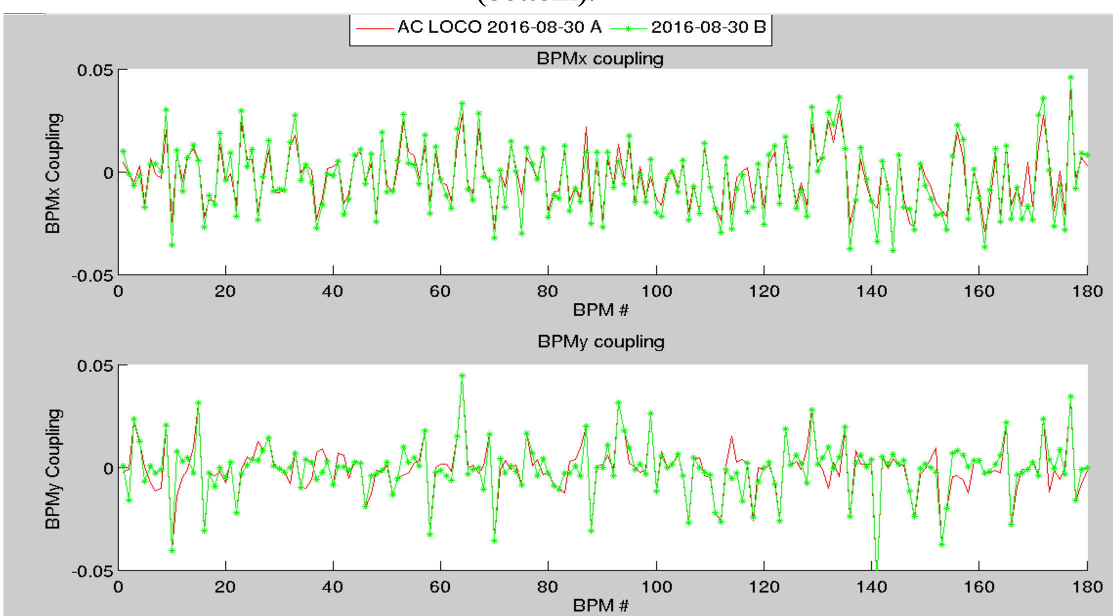

Fig. 6. Measured BPM couplings: horizontal (top) and vertical (bottom).

Numerical Investigation of the BPM Calibration Precision

The following investigations are explored for a better understanding on the precision of the BPM calibration:

1. G_x: Multiply the first row of the measured ORM, $ORM_{1,\,j}$, which corresponds to the first horizontal BPM, by a factor of a (= 1.05, 1.1, and 1.3), and find out how well the BPM gain [$G_x(1)$] in the LOCO analysis reflects this multiplier a (the real gain). Here, j = 1, 2, …, 180, is the index of all horizontal corrector magnets [equation (1)].
2. G_y: Multiply the 181th row of the measured ORM, $ORM_{181,\,j}$, which corresponds to the first vertical BPM, by a factor of a (= 1.05, 1.1, and 1.3), and find out how well the BPM gain [$G_y(1)$] reflects it. Here, j = 181, 182, …, 360, is the index of all vertical corrector magnets.
3. G_{xy}: Multiply $ORM_{181,\,j}$ by a factor of a (= 0.005, 0.01, and 0.02) and add it to $ORM_{1,\,j}$ [$ORM_{1,\,j}' = ORM_{1,\,j} + a \cdot ORM_{181,\,j}$], and find out how well the horizontal BPM coupling [$G_{xy}(1)$] reflects the multiplier a. Here, j = 181, 182, …, 360.
4. G_{yx}: Multiply $ORM_{1,\,j}$ by a factor of a (= 0.005, 0.01, and 0.02) and add it to $ORM_{181,\,j}$ [$ORM_{181,\,j}' = ORM_{181,\,j} + a \cdot ORM_{1,\,j}$], and find out how well the vertical BPM coupling [$G_{yx}(1)$] reflects it. Here, j = 1, 2, …, 180.

The result of the first investigation is shows in figure 7. The gain error (dG_x / K_x) of the first horizontal BPM is within +/-0.007% (indicated by the two green dashed lines) when the BPM gain K_x is in the range 0.95 to 1.05 determined by the LOCO measurement (see top plots in figures 2 and 5). Here, K_x (= a) is the real BPM gain and G_x is the LOCO fitted BPM gain. The gain error dG_x / K_x is defined as (G_x - K_x) / K_x. The result of the second investigation is shows in figure 8. The gain error (dG_y / K_y) of the first vertical BPM is within +/-0.06% when the BPM gain K_y is in the range 0.95 to 1.05 (bottom plots of figures 2 and 5). Although the vertical BPM gain errors are ten times larger than the horizontal BPM gain errors, they are still very small.

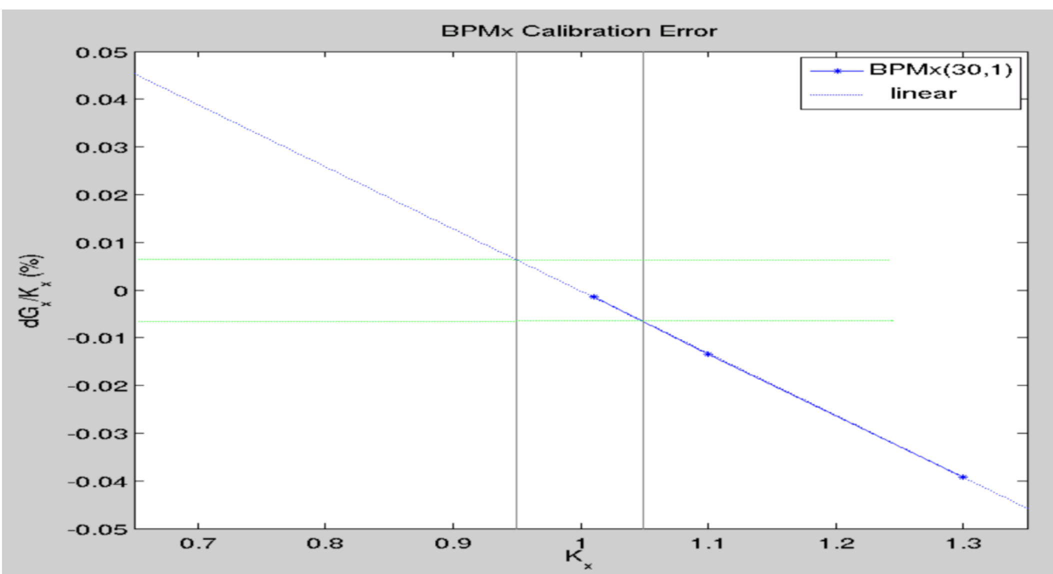

Fig. 7. The gain error of the 1st horizontal BPM dG_x / K_x (%) as a function of the BPM gain multiplier K_x.

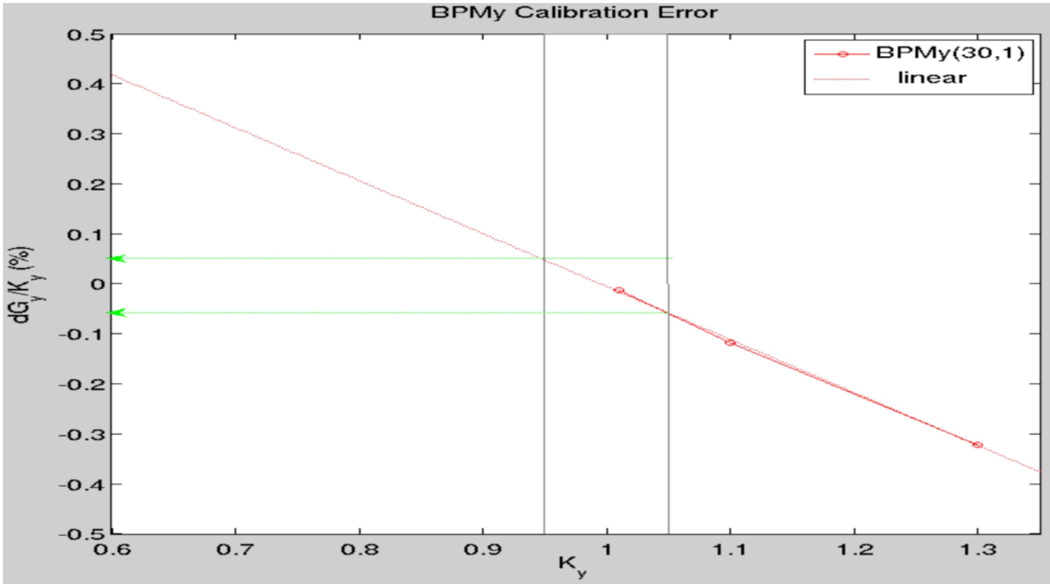

Fig. 8. The gain error of the 1st vertical BPM dG_y / K_y (%) as a function of the BPM gain multiplier K_y.

Due to degeneracy only existing in the vertical BPM gain calibration, which will be described later in the note, the average gain of all BPM_y can be quite different from one by a constant factor. Therefore, we decide to fix the degeneracy problem by keeping the average gain of all BPM_y to be one, called the BPM_y gain correction.

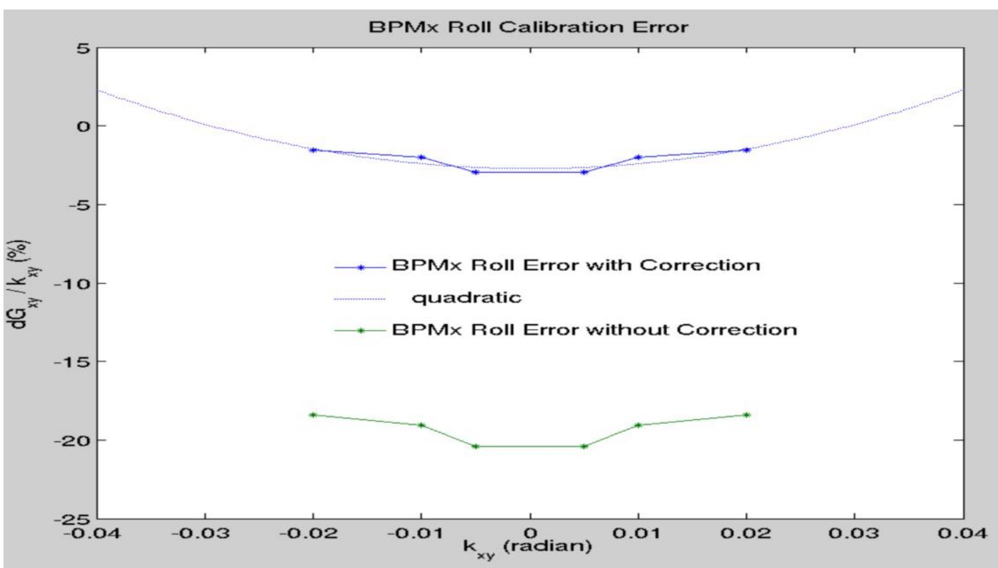

Fig. 9. The coupling error of the 1st horizontal BPM dG_{xy} / K_{xy} (%) as a function of the BPM coupling multiplier K_{xy} with (blue) and without (green) the BPM_y gain correction.

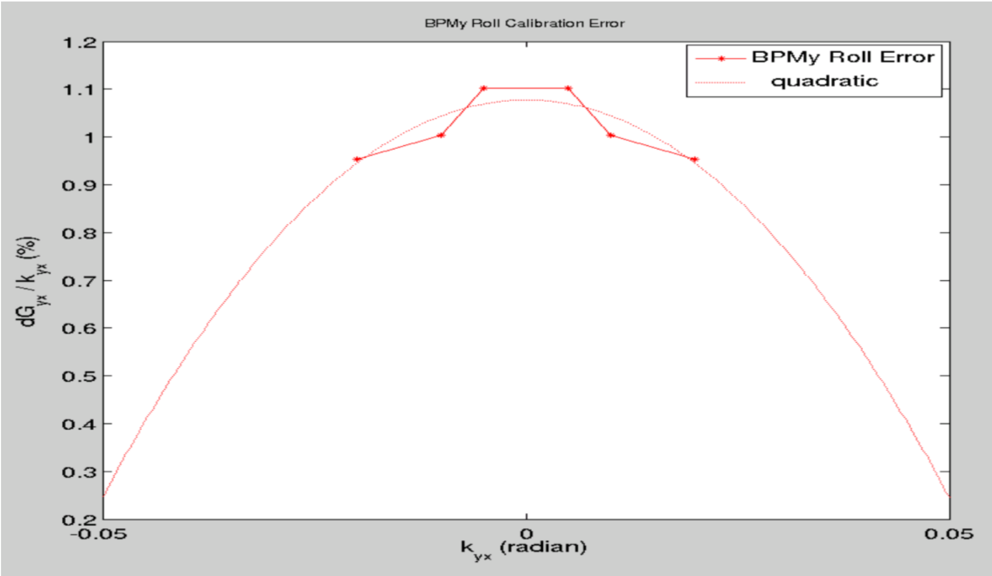

Fig. 10. The coupling error of the 1st vertical BPM dG_{yx} / K_{yx} (%) as a function of the BPM coupling multiplier K_{yx}.

The BPM_x coupling error without the BPM_y gain correction is shown as the green curve in figure 9, and it is significantly different from the real coupling K_{xy}. However, once including the BPM_y gain correction, the BPM_x coupling error becomes the blue curve and agrees well with K_{xy}. ***It is evident that the BPM_y gain correction is needed for the reliable BPM_y gain and BPM_x coupling calibrations.*** The BPM_y coupling error dG_{yx} / K_{yx} as a function of the BPM_y coupling (K_{yx}) is shown in figure 10. There is no need for the BPM_x gain correction for the reason, which will be mentioned in the next section.

Overcome Degeneracy

There is degeneracy in the LOCO analysis if we only include the response to steering magnets. We can scale up all the BPM gains (G_y) and scale down all the steering magnet calibrations ($\Delta y'$), and the ORM does not change [equation (2)].

$$\Delta y(s) = G_y(s) \cdot \Delta y'(s_0)\sqrt{\beta_y(s_0)\beta_y(s)}\ \frac{\cos[|\psi_y(s)-\psi_y(s_0)|-\pi\nu_y]}{2\sin\pi\nu_y} \quad (2)$$

This degeneracy is eliminated in the horizontal plane when we include the dispersion in the LOCO fit since we know to very high accuracy how much we changed the RF frequency when measuring the dispersion. The dispersion measurement fixes the overall absolute horizontal BPM gain scaling, whereas fitting the ORM without including the dispersion just gives the relative gain variation between BPMs.

With a decoupled ring, or with small coupling, the overall scaling factor for the vertical BPMs is not well constrained. We can calibrate the vertical BPM gains by measuring the ORM after using the skew quadrupoles to increase the coupling. With large coupling the dispersion measurement constrains both the horizontal and vertical gains overall scaling factor.

For the purpose of taking advantage of the well calibrated RF 'kicker' to remove the uncertainty of the BPM_y gains, we numerically investigate how the ring coupling influences the BPM_y gain calibrations. Three sets of the LOCO simulations have been done at 0.0%, 0.29%, and 0.95% couplings.

In the LOCO analysis, we deliberately add 30% and 60% vertical corrector calibration errors to each set of the LOCO data, therefore total six cases, and find out how the vertical corrector calibration error influences the average BPM_y gain. The average BPM_y gain as a function of iteration is shown in figure 11. It is clear that when the coupling (C_{xy}) is 0.0%, the average BPM_y gain is undetermined and the error is large; when C_{xy} = 0.29%, the BPM_y gain error is ~(0.6% to 0.8%), and when C_{xy} = 0.95%, the error is reduced to ~0.19%.

When the lattice coupling error is small (~0.0%), the vertical corrector calibration error reflects onto the vertical BPM gain calibration error. Therefore, we couldn't get reliable calibrations for both vertical correctors and BPM_y. Guided by the numerical study, we should be able to overcome the BPM_y gain uncentrainty to ~0.2% by increasing the lattice coupling to ~1%. Similary, we examine the vertical corrector calibration (figure 12) for those six cases, the right value should be 0.012 rad/A. In the coupling 1% case, the LOCO analysis also provides the right calibration for the vertical correctors.

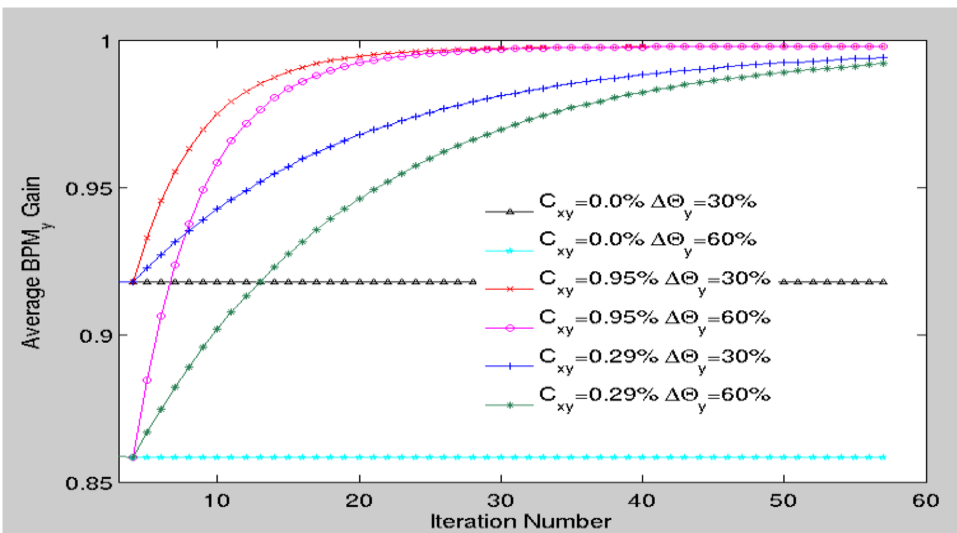

Fig. 11. The average vertical BPM gain as a function of iteration at those 6 cases.
C_{xy} = 0.0% and 30% vertical corrector calibration error ($\Delta\Theta_y$) (black);
C_{xy} = 0.0% and $\Delta\Theta_y$ = 60% (cyan);
C_{xy} = 0.29% and $\Delta\Theta_y$ = 30% (blue);
C_{xy} = 0.29% and $\Delta\Theta_y$ = 60% (green);
C_{xy} = 0.95% and $\Delta\Theta_y$ = 30% (red);
C_{xy} = 0.95% and $\Delta\Theta_y$ = 60% (magenta).

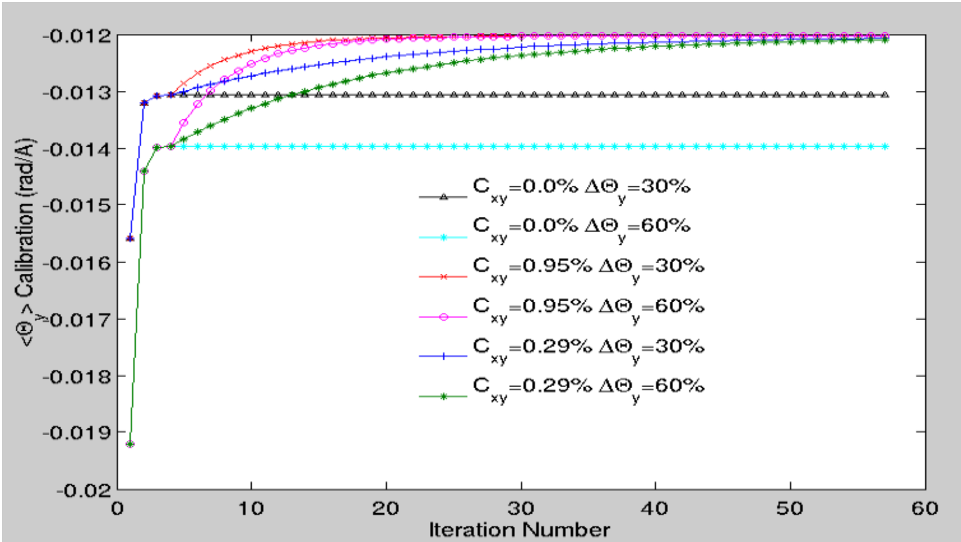

Fig. 12. The average vertical corrector calibration as a function of iteration at those 6 cases.

Avoid Fitting Parameter Cross-talks

By introducing a sufficient amount of the coupling (~1%) *via* skew quadrupoles, the degeneracy problem between the average BPM_y gain and corrector calibration is resolved to an uncertainty of the average BPM_y gain ~0.2% (see figure 11). Afterwards, the next significant error source comes from the cross talk between different fitting parameters.

By analyzing the correlation of the vertical BPM gain and coupling (roll) (indexed as i = 1, 2, …, 180) with all the LOCO fitting parameters (indexed as j = 1, 2, …, 1260) defined by equation (3) in 0.0% and 0.95% couplings, the results are shown in figure 13.

$$\rho_{ij} = \frac{J_i^T \cdot J_j}{\|J_i\| \cdot \|J_j\|} \qquad (3)$$

In the 0.95% coupling case, the BPM_y gain (bottom right) and coupling (bottom left) have cross talks with more LOCO fitting parameters compared to the zero coupling case (top right and left plots). Here, J is the Jacobian [1].

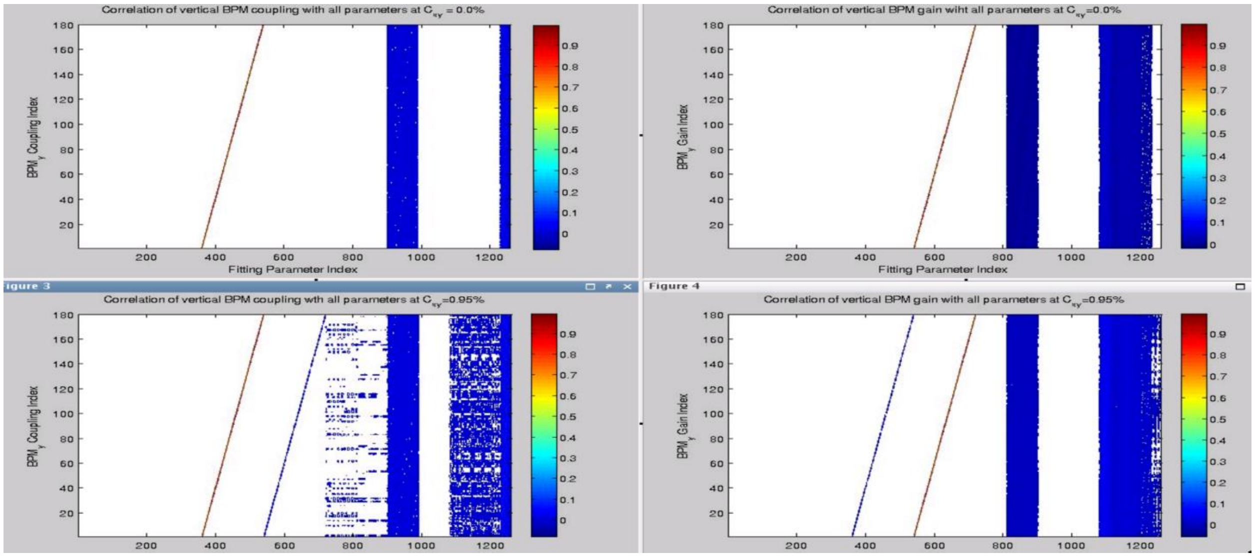

Fig. 13. The BPM_y gain (bottom right) and roll (bottom left) in the 0.95% coupling case, and the BPM_y gain (top right) and roll (top left) in the zero coupling case.

We expect that cross talks contribute additional BPM calibration errors. Figure 14 shows the BPM_y gains in 0.0% (blue) and 0.95% (red) couplings, which should be one in both cases. The BPM_y gains in the 0.95% coupling case have comparably larger errors than the case with zero coupling. A well corrected linear lattice should be able to minimize the cross-talks.

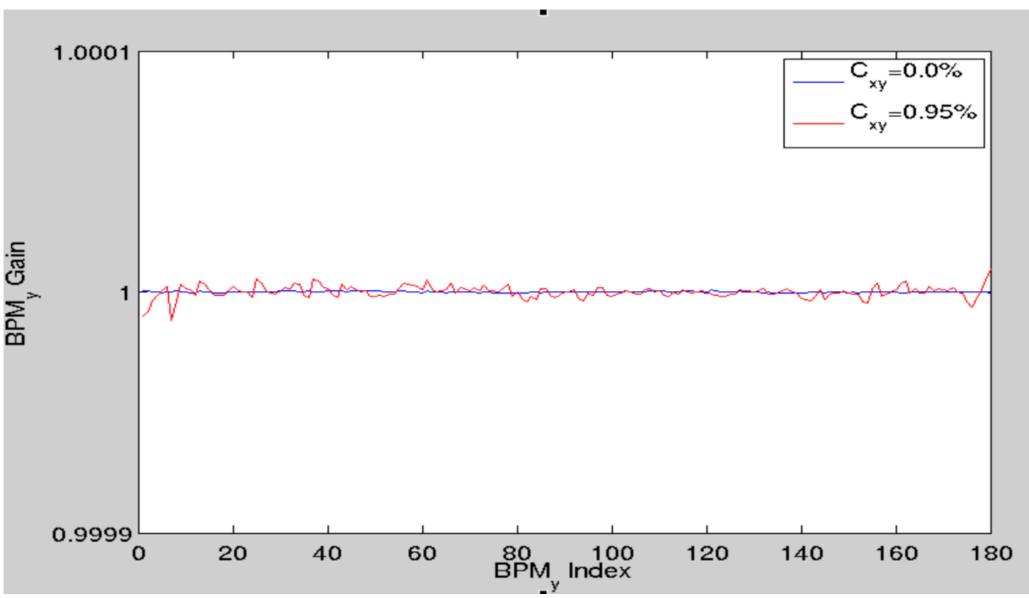

Fig. 14. The BPM_y gain in two different coupling cases 0.95% (red) and 0.0% (blue).

Comparision of DC and AC LOCO Results

We performed the side-by-side comparison of DC LOCO and AC LOCO for the BPM calibrations on April 9th, 2017. Two sets of DC LOCO data, one with 0.03% coupling and the other with 2.72% coupling. AC LOLO measurement is performed only once at the 0.03%

coupling. They agree reasonably well after the BPM_y gain correction, except the BPM_y coupling. Figure 15 shows the BPM_x (top) and BPM_y (bottom) gains respectively. Figure 16 shows the BPM_x (top) and BPM_y (bottom) couplings.

Indeed, at the coupling 2.7% case, the average BPM_y gain is close to one; however, at the coupling 0.03% case, it equals to 0.9544, a significant deviation from one [Table I].

Even when the BPM_y couplings obtained from AC LOCO and DC LOCO are different [bottom plot in figure 16], after applying the BPM calibrations to the same dispersion measurement, the results are the same. The horizontal (top) and vertical (bottom) dispersions are shown in figure 17. The direct measurements are shown as the red curves. The dispersions after applying the BPM calibration *via* AC LOCO (blue) agree extremely well with the dispersions after applying the BPM calibration *via* DC LOCO (green).

Table I. BPM calibrations from DC LOCO1, DC LOCO2, and AC LOCO

	G_x	G_y	G_{xy}	G_{yx}	Coupling (%)	$\Delta\beta_x/\beta_x$ (%)	$\Delta\beta_y/\beta_y$ (%)
DC LOCO1	0.9953	0.9544	-0.004	-0.0012	0.03	1	1
DC LOCO2	0.9947	1.0074	-0.004	-0.0013	2.7	1	1
AC LOCO	0.9953	1.0655	-0.004	-0.00056	0.03	1	1

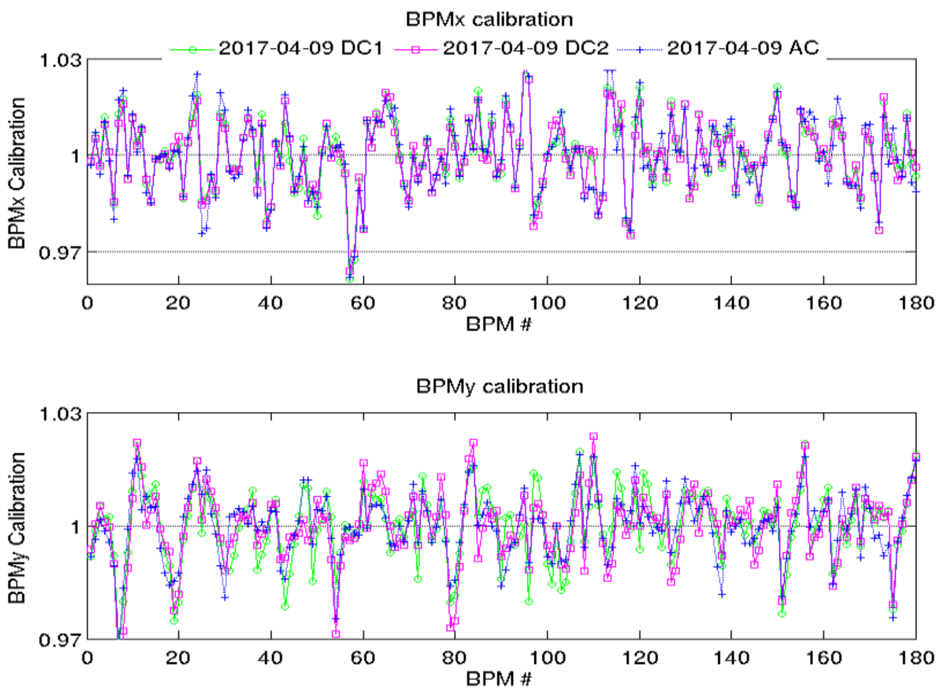

Fig. 15. Measured BPM gains *via* DC LOCO and AC LOCO techniques: horizontal (top) and vertical (bottom).

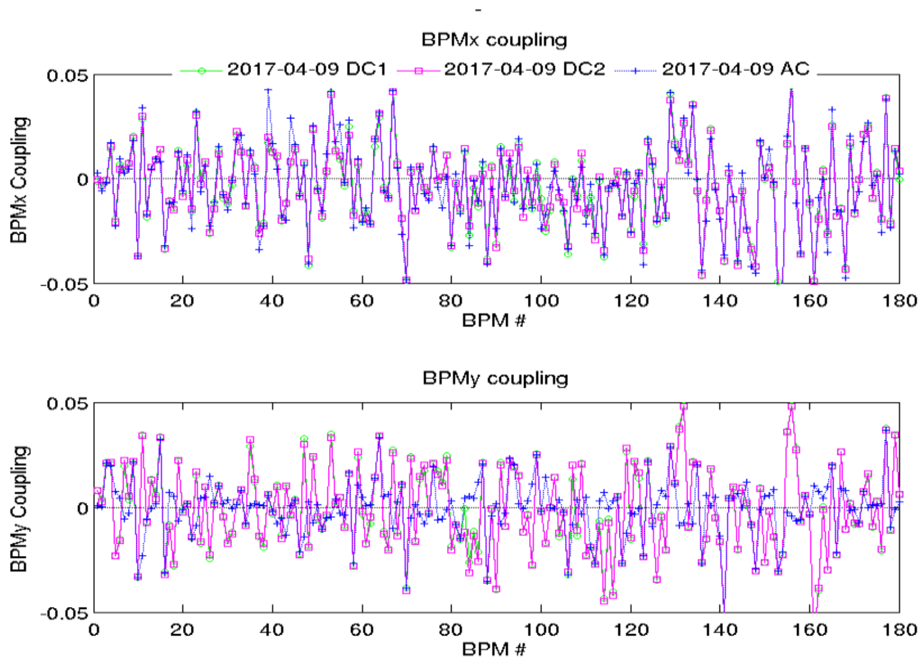

Fig. 16. Measured BPM couplings *via* DC LOCO and AC LOCO techniques: horizontal (top) and vertical (bottom).

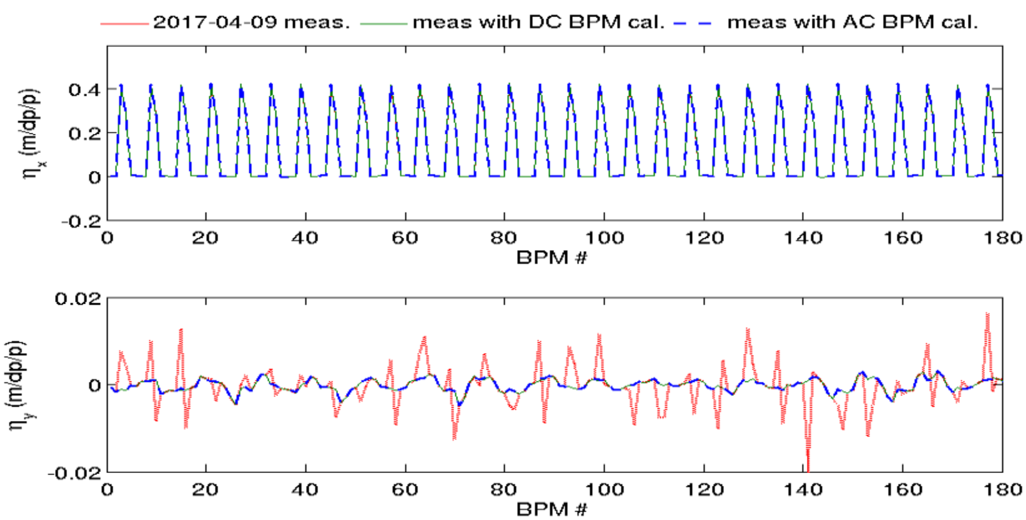

Fig. 17. The horizontal (top) and vertical (bottom) dispersions from the direct measurement (red), the one after applying the BPM calibration *via* AC LOCO (blue), and the one after applying the BPM calibration via DC LOCO (green).

Procedure for BPM Calibrations

- Correct linear lattice with the residual beta beating to ~1% level
- Increase the coupling *via* a skew quadrupole, prefer even-cell one, ΔI = 10A
- Obtain the average BPM_y calibration from the first LOCO measurement
- Correct the coupling
- Perform the second LOCO measurement for individual BPM calibrations

Conclusion

As the result of those investigations, BPM calibration *via* the LOCO analysis appears to be precise enough for being implemented to the NSLS-II SR BPM system. At the first step, we should deliberately increase the coupling to take care of the degeneracy problem existing in the BPM_y calibration, therefore achieving the precision of the average BPM_y calibration. Afterwards, we should reduce the coupling *via* the skew quadrupole correction and minimize the cross-talk among different LOCO fitting parameters *via* improving the linear lattice, as the result, further improving the precision of each individual BPM calibration. Normally, the first step is only applied in the stage of commissioning the BPM system. Afterwards, scaling the average BPM_y gain to one is routinely used to replace the first step when the coupling is small.

We have applied the above procedure to the BPM calibration. As the result, the measured dispersion agrees very well with the predicted dispersion *via* the LOCO fitted machine lattice when the BPM calibration is applied to the measurement. Therefore, by applying the BPM calibration *via* the LOCO technique, we can obtain the real dispersion measurement of the live machine directly from the calibrated BPM readings. Besides, the coupling correction and control should become much more robust and reliable in the daily operation.

Acknowledgements

We gratefully acknowledge useful discussions with J. Safranek and V. Sajaev.

References

[1] J. Safranek, "Experimental determination of storage ring optics using closed orbit response measurements", Nucl. Instr. Meth. A388, p. 27, 1997.

[2] X. Yang, "Applying Matlab LOCO to the NSLSII Storage Ring Commissioning", NSLS-II Technical Note #131.

[3] X. Yang, V. Smaluk, L.H. Yu, Y. Tian, K. Ha "AC LOCO: a fast and precise technique for magnet lattice correction", submitted to PRSTAB.