STORAGE RING BEAM DYNAMICS MODELING WITH LIMITED INSTRUMENTATION

C. Kwankasem, SLRI, Nakhon Ratchasima, Thailand
S. Chunjarean[#],Suranaree University of Technology, Nakhon Ratchasima, Thailand

Abstract

For the SIAM Photon Source (SPS), we propose to establish a storage ring model based on quadrupole fitting of the measured betatron functions, a series of problems at the SPS could be determined. For example, the problem of turn-to turn electrical coil shorts was detected and solved by replacing new quadrupole coils. Subsequently, we could identify a quadrupole calibration error due to conflicting information on the number of turns per coil. Other causes regarding the beam dynamics model such as high field saturation effects, power supply calibration error, and proximity to nearby magnets have been taken into account to establish accurate quadrupole calibration factors. The establishment of an accurate model is essential for beam dynamics predictions, closed orbit correction, response matrix determination for LOCO, low emittance operation and optics correction for high field insertion devices.

INTRODUCTION

The Siam Photon Source (SPS) emerged from storage ring SORTEC [1] which was decommissioned and upgraded to optimize its use as a radiation source. The SPS storage ring had a four-fold symmetric lattice with four long straight sections. Each symmetric lattice [2] consisted of 4 focusing (QF), 4 defocusing (QD) quadrupole and 2 bending magnets. Such a combination of magnets as shown in Fig.1 is called a Double Bend Achromat (DBA) lattice. During re-commissioning it was possible to store an electron beam in excess of 200 mA, but only after an hour of warm-up time for the magnets and after that beam was still lost frequently at random times without obvious cause [3]. To inject and store beam, it was also necessary to utilize at some locations unreasonably strong beam steering which alone would have caused orbit distortions larger than the acceptance of the vacuum chamber aperture.
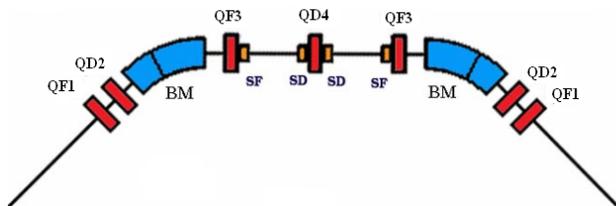
Figure 1: DBA lattice for the SPS storage ring. QF1 and QD2 quadrupoles were original quadrupoles from the SORTEC and the QF3 and QD4 are newly manufactured with mechanical dimensions equal to the original ones.

_____
[#]chunjarean@gmail.com

Successful operation and optimization of a storage ring requires the knowledge of a reliable theoretical beam dynamics model, which makes it possible to, for example, correct for perturbations from insertion devices, improve the ring performance or to perform predictable closed orbit correction. A reliable model implies that setting the actual strengths of quadrupoles in the storage ring equal to theoretical predictions will lead to measurable beam dynamics quantities which agree with the theoretical model predictions. Most methods to detect beam dynamics errors, however, rely on functioning and well calibrated BPMs. One might apply the widely used program LOCO [4] to detect and correct calibration errors by orbit response matrix measurements. However this measurement requires a fully functioning BPM system which is not yet the case at the SPS. An alternative method to establish a workable model is described here based on fitting quadrupole strengths to measured betatron and dispersion functions.

LATTICE STRUCTURE ANALYSIS

Betatron function measurements

The betatron functions were measured at each quadrupole magnet by measuring the tune shifts due to a small change of the quadrupole strength. The value of the betatron functions are then given by

$$\beta(s) = \frac{4\pi}{N} \cdot \frac{B\rho}{gl_{eff}} \left(\frac{\Delta \nu}{\Delta I/I} \right) \qquad (1)$$

where $\beta(s)$ is the betatron function, $\Delta \nu$ the tune shift, gl_{eff} the integrated quadrupole gradient, and $\Delta I/I$ the relative change in total excitation current.

To establish a real beam dynamic model relied on the theoretical model the betatron functions were measured in the theoretical configuration with beam emittance of 72 nm and beam energy of 1.0 GeV. A comparison of the measured with theoretical betatron functions is shown in Fig.2. From asymmetries of the betatron functions in both horizontal β_x and vertical β_y plane there was a problem in individual quadrupole. By trial and error the largest asymmetries of the betatron functions caused by only a few QF1 and QD2 pointing turn to turn electrical shorts in the quadrupole coils. "Cold" resistance measurements did not give conclusive results, but resistance measurements on "warm" quadrupoles revealed electrical turn-to-turn leakages or outright electrical turn-to-turn shorts in many of the old quadrupole coils.
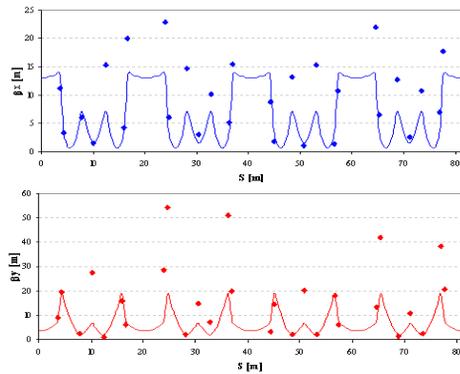
Figure 2: Measurement of the horizontal (blue dots) and vertical (red dots) functions comparison with the theoretical 72 nm configuration (solid lines) for the SPS storage ring.
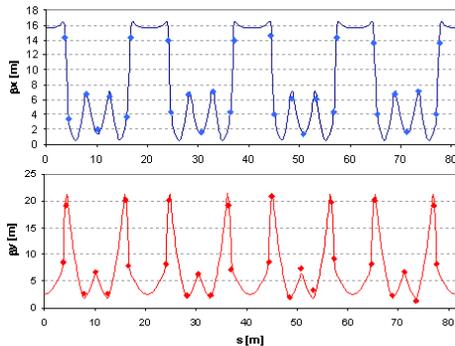
Figure 3: Theoretical (solid lines) and measured (dots) betatron functions after replacement of all QF1 and QD2 quadrupole coils.

New quadrupole coils

After replacement of the coils, it was not possible to readily inject. However only increasing the excitation currents in the quadrupoles (QF1, QD2) with the new coils by some 4 % was it possible to inject again. This empirical recalibration allowed storage ring operation but has not been explained up to now. For whatever the beam dynamics configuration was at that time, betatron functions measurements confirmed that the storage ring stability and symmetry was fully restored shown in Fig. 3.

Number of turns per excitation coil

Although a symmetric ring was achieved again, a 4% systematic empirical change in the quadrupole calibration had to be applied to the quadrupole with the new coils. Therefore the magnet strength calibration used to translate excitation currents to field measurements had to be checked. There were conflicting data in available documents on the number of turns in the quadrupole excitation coils. The design drawing for the original quadrupoles indicates 24 turns, yet the experimental excitation curves are only consistent with 25 turns. Only visual inspection of one old coil revealed that the coils consisted of 25 turns. The new coils have only 24 turns and parameters in the control program assuming 25 turns

had to be changed accordingly. The difference in turns has never been included in the control program and is obviously responsible for the so-far unexplained ~4% empirical change in calibration. In the absence of new magnetic measurements, we assume for the beam dynamics model in the following discussions a corrective scaling by the factor 25/24 on the excitation currents for the QF1 and QD2.

Magnet saturation

All quadrupole field integrals had been measured by the magnet manufacturers at either 400 or 500 Ampere where there is already significant saturation. For lower field strengths, the excitation current was erroneously scaled linear therefore resulting in too weak a focusing. Nonlinear adjustments of magnet calibrations are required to take into account saturation effects especially for operation at 1.2 GeV. Based on the original magnetic field excitation measurements a nonlinear two-component polynomial fit was applied to the magnet excitations well into saturation. At low excitation, well constructed magnets must be linear. The polynomials are for a measured effective magnet length of 0.323m common to all quadrupoles following by

$$QF1: g(T/m) = 0.02633I - 1.035 \times 10^{-20} I^7$$
$$QD2: g(T/m) = 0.02637I - 1.035 \times 10^{-20} I^7$$
$$QF3: g(T/m) = 0.02631I - 1.289 \times 10^{-19} I^7 \qquad (2)$$
$$QD4: g(T/m) = 0.02630I - 1.218 \times 10^{-19} I^7$$

The linear coefficients are equal within less than a percent as expected from equal mechanical geometries while the saturation becomes effective only at high excitation currents and reflects two different iron qualities used in the old (QF1,QD2) and new (QF3,QD4) quadrupoles.
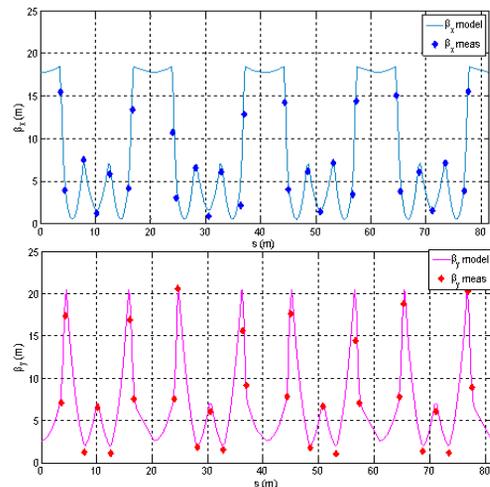
Figure 4: The 28 nm (1 GeV) low emittance configuration (solid lines: model, dots: measurement).

Beam Dynamics and Electromagnetic Fields

Energy calibration

For bending magnet the excitation measurements which reach only up to 1300 A corresponding to 1 GeV, the excitation polynomial including saturation of

$$B = 0.0009134I - 6.6 \times 10^{-18}I^5 \text{ (for I} < 1300 \text{ A)} \quad (3)$$

From the excitation polynomials, the actual excitation currents during betatron function measurements define the magnet strengths that should be used in a theoretical model. Both model and measurement as shown in Fig. 4 presents the restored symmetry of the storage ring lattice.

RESULTS AND DISCUSSIONS

Encouraged by the restoration of symmetry and relative close match between model and storage ring, we implemented a new lattice configuration at the SPS which promised a significantly lower beam emittance. The main goal was to reduce the beam emittance for the original lattice configuration [2] of 72 nm at 1 GeV. The SPS lattice is based on a four-fold DBA structure for which the theoretical lowest beam emittance is 51 nm at 1 GeV. Removing the condition that the lattice unit be an achromat, it is known that an even smaller beam emittance can be achieved. Studies in this direction have been done and a configuration with an equilibrium emittance of 28 nm at 1 GeV can be achieved resulting in a seven-fold increase in photon beam brightness [5]. This lattice was implemented with the calibrations known at that time as discussed above and the betatron functions were measured and shown in Fig.4. The measured betatron functions agree very well with the theoretical values, while the measured tunes of $\nu_{x,y}$=4.74/2.83 are close to the theoretical tunes of $\nu_{x,y}$= 4.72/2.89 considering that the close orbit has not yet been corrected. To obtain a precise theoretical model, possible errors in quadrupole power supply calibration must be considered. The QF3/QD4 power supply calibration though revealed some calibration error at the expected level of almost a percent. At this moment the power supplies recalibrations have not yet been performed for all power supplies to avoid interference with ongoing operation for users. Furthermore, QF3 and QD4 are located close to sextupoles and magnetic field interference can be suspected.
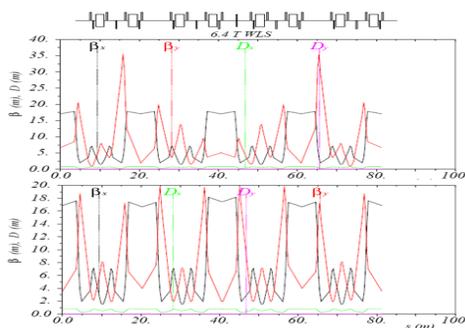
Figure 5: Perturbation of twiss functions by 6.4 T WLS at 1.2 GeV before (up) and after (low) correction.

CONCLUSION

From elimination of beam dynamic errors by small steps, guided by fitting of quadrupole strength parameter to measured the betatron and dispersion functions, a series of problems of the SPS storage ring could be identified which had to be corrected or must be taken into account (change in number of turns in the new coils, saturation, power supply calibration, proximity to nearby magnets) to develop a theoretical lattice model responding well the actual storage ring beam dynamics. Establishment of an accurate model is not only of aesthetic value but allows more accurate predictions for beam dynamics issues like, for example, closed orbit correction, determination of the response matrix for LOCO, insertion of high field IDs and their corrections, new lattice configuration to reach lower beam emittance etc. For the SPS we have arrived at a model which describes fairly well the actual beam dynamics and provides now a sound basis for effective optimization and final correction with the LOCO approach. Having a theoretical model which agrees well with the actual storage ring allows us to confidently design corrections of perturbations caused by the installation of high field insertion devices, for example a 6.4 T Wave length Shifter (WLS). The WLS will be installed but it causes significantly perturbation of the vertical beam dynamics which must be compensated by adjustments of nearby quadrupoles. Matching of the betatron and dispersion functions to the nearby unit cells and readjustment of the overall tunes restored almost perfectly the unperturbed configuration. In Fig. 5, the vertical betatron function in the vicinity of the wavelength shifter is shown before and after correction of the perturbation on betatron and dispersion functions [6].

ACKNOWLEDGMENTS

REFERENCES

[1] M. Kodaira, et.al., Jap. Jour. of Appl. Phys., 30, No. 11B, (1991) 3043.

[2] P. Kengkan, et.al., Jounal of Synchrotron Radiation, 5, (1998) 348.

[3] S. Rujirawat, et.al., "The 5th Asian Synchr.. Rad. Forum", Saga, Japan5, (2004).

[4] J. Safranek, Nucl. Inst. and Meth. A388, pp. 27-36, (1977).

[5] S. Chunjarean, "Low emittance study for 1.0 GeV SPS storage ring", NSRC-TN-2004/07, (2004).

[6] C. Kaewprasert, "Effect of the 6.4 T Max-Wavelength Shifter on 1.2 GeV SPS ring", NSRC-TN-2005/05-1, (2005).