ANALYSIS OF NONLINEAR EFFECTS OF IDS AT THE SPS STORAGE RING*

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Abstract

To generate intense and high energy synchrotron radiation at the Siam Photon Source (SPS) 1.2 GeV storage ring, two insertion devices (IDs), namely, a 2.2 T hybrid multipole wiggler (MPW) and a 6.5 T superconducting wavelength shifter (SWLS), have been installed and operated since 2013. The angular kicks due to the nonlinear effects generated by the IDs represented by kick maps were used in our analysis. The optics distortion was compared to the ones obtained from calculation using hard-edge model and measurement results. In order to investigate the effects of IDs on the beam dynamics, Frequency Map Analysis (FMA) was employed. The effects of the IDs and their compensation are presented herewith.

INTRODUCTION

Since 2013, two insertion devices (IDs) have been installed and operated in the SPS storage ring to produce higher intensity and higher energy synchrotron radiation [1]. However, up till now the SWLS has been operated only at 4.0 T, despite the peak field of 6.5 T, due to the limitation of the existing RF system. Electron beam is injected into the storage ring at 1.0 GeV with SWLS at 4.0 T and MPW gap opened. The beam is then ramped up to 1.2 GeV, and the MPW gap is closed afterwards. The electron beam is filled twice a day. The electron orbit is restricted within 10 microns by a Slow Orbit Feedback (SOFB) system. In normal operation, the electron beam is stored with a maximum current of 150 mA and decays to 60 mA after 11.5 hours. At the moment, it is not possible to inject the beam when the MPW gap is closed down to 23.5 mm (minimum gap). Even though the beam optics was corrected following ID installation, nonlinear effects still remain.

We plan to upgrade the booster synchrotron and the high-energy beam transport to 1.2 GeV for full-energy injection and subsequently top-up operation. Then, the electron beam has to be injected with the MPW gap closed. The good field region of the MPW has to be increased for injection with a small gap. In addition, we found that the coupling value gets larger compared to the time before ID installation. In order to increase the beam brightness, the coupling must be reduced. Therefore, the skew quadrupole field of the IDs needs to be measured and studied.

METHODS FOR ID MODELING

A model calculation is used to explain the dynamics of the electron beam passing though an insertion device. This paper employs the following methods:

Hard-edge model [2]: The magnetic field distribution of an ID can be represented with that of a hard-edge model. In this work, each magnet is separated into five pieces (piecewise hard-edge model). The edge focusing effect of IDs can be simulated by small dipole magnets. This model is then used in MAD-X simulation code.

Kick-map [3]: The kick-map describes the kicks an electron gets while traversing an ID. It is derived from the potential which is calculated by integrating the magnetic field of the ID for tracking calculations. The nonlinear kick-map is generated from RADIA code. Both the linear and nonlinear effects are included.

EFFECTS FROM INSERTION DEVICES

Linear Effects

The betatron tunes of the design lattice were $\nu_x = 4.768$ and $\nu_y = 2.813$. The maximum betatron functions were 15.3 m and 19.8 m for the horizontal and vertical directions, respectively. After ID installation, the betatron functions were disturbed and the symmetry of the ring was broken. The tune shifts, calculated from the hard-edge model and the kick-map, as well as obtained from measurement, are listed in Table 1. The calculated vertical tune shifts from the two methods agree quite well with the measurement. However, this is not the case for the horizontal tune.

The measured horizontal tune shift introduced by the MPW is in agreement with the kick-map prediction while the simple hard-edge model cannot calculate the tune change. However, the tune shift and beta-beating are compensated by global and local quadrupole magnets. The beam optic distortions have been successfully restored to nominal values with the use of Linear Orbits from Close Orbits (LOCO) code.

Table 1: Tune shifts ($\Delta\nu_x$, $\Delta\nu_y$) introduced by the 2 IDs calculated from hard-edge and kick-map models, as well as the ones obtained from measurements.

IDs	2.2 T MPW	6.5 T SWLS
Hard-edge	0.00, 0.047	0.00, 0.120
Kick-map	-0.016, 0.035	-0.008, 0.112
Measurement	-0.024, 0.037	-0.040, 0.106

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Nonlinear Effects

Linear effects from IDs in the vertical direction are generated by edge focusing, which is a function of field strength and period length, while the horizontal focusing is introduced by field roll-off and finite pole width. If the good field region is not sufficiently large, nonlinear effects will be produced. These nonlinear effects can be represented by angular kick-map, which is used for dynamic tracking with the ELEGANT code [4].

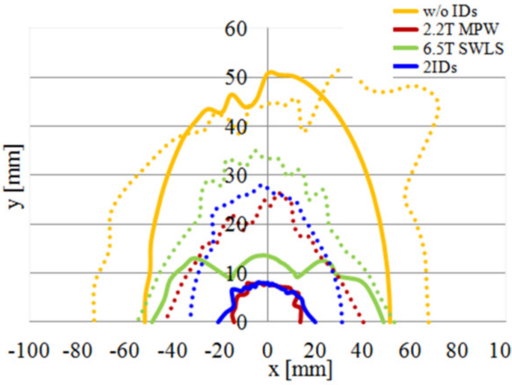

Figure 1: Comparison of dynamic apertures calculated from the hard edge model (dotted line) and the kick-map (solid line).

The dynamic aperture (DA) in the case of 2 IDs (blue line) decreases by 50% according to the hard-edge model, and by more than 75% according to the kick-map, as nonlinear effects are included (Fig. 1). It can be seen that the reduction in the DA comes predominantly from the MPW. Nonlinear effects caused by the MPW inevitably lead to lifetime reduction and slow injection**.**

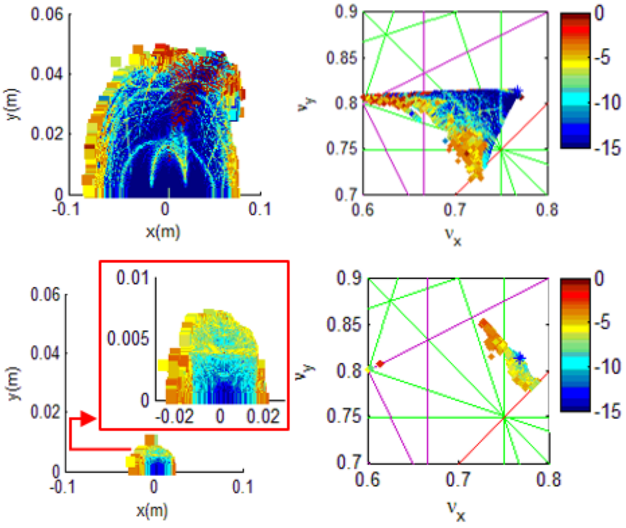

Figure 2: In these graphs the color indicates the beam dif- fusion rate. The beam position (left) and the frequency map (right) for the case without IDs are on the top, while the ones for the case with the 2 IDs installed are on the bottom.

Frequency Map Analysis (FMA) [5] has been used to study the relationship between the betatron tunes, the beam phase-space, and the survivability of the beam, in order to minimize nonlinear effects, and subsequently identify the optimal operating point. The FMA is employed in particle tracking simulations to detect chaotic motion and to calculate the beam diffusion rate, which leads to beam loss.

In Fig. 2, the two graphs on the top show the diffusion (left) and the FMA (right) when there is no ID. The corresponding graphs with two IDs installed are presented at the bottom. Blue color represents the area where the electron motion is stable and the beam can survive. It is significantly reduced after the two IDs were installed. Red color represents the area where the motion of the electron becomes chaotic, leading to high diffusion rate. The electrons may be lost due to large scattering amplitude. The electron motion is excited when the tune crosses the fourth order resonance lines as well.

Injection with MPW Gap Closed

For the SPS storage ring, the injected beam is horizontally offset by 42 mm from the stored beam when it enters the ring, and the MPW is located in the injection section. At present, the beam cannot be injected when the MPW gap is less than 40 mm. The horizontal DA becomes too small for injection when the MPW gap is closed to 23.5 mm. The good field regions are ±5 mm and ±17 mm for the MPW and the SWLS, respectively, which is part of the reason why the injection can be accomplished with the SWLS but not with the MPW. The nonlinear field can be minimized by shimming or implementing magic fingers [6].

ELECTRON BEAM MEASUREMENTS

Multipole Field of IDs

In these measurements, the storage ring was operated with the 2.2 T MPW and the 6.5 T SWLS. To observe the multipole field of the IDs [7], the horizontal tune were measured and fitted in power expansion as a function of horizontal orbit bump both in the MPW and the SWLS (Fig. 3). Two effects were considered. The first is the horizontal tune shift introduced by the IDs, which is represented by the quadrupole integral field in x component. This was found to be 2.263 m^{-1} in the case of the SWLS, and 0.348 m^{-1} for the MPW. This explains why the measured horizontal tune shift is higher for the SWLS, as listed in Table 1. Secondly, the DA is reduced by the nonlinear terms which are generated in the sextupole and octupole integral fields. For the octupole term, this is represented by an x^3 component, which was found to increase from -505.05 m^{-3} in the case of no ID, to -33,238.84 m^{-3} for the MPW and -23,148.15 m^{-3} for the SWLS.

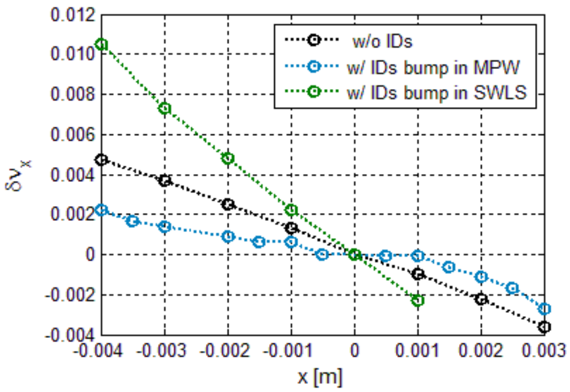

Figure 3: Horizontal tune shift as a function of horizontal orbit bump in the MPW and the SWLS.

Coupling Control

The coupling between horizontal and vertical planes leads to vertical emittance via horizontal betatron oscillation and vertical dispersion. Horizontal oscillation leads to oscillation in the vertical plane, and the nonzero vertical dispersion increases the vertical emittance by quantum excitation. Thus the vertical beam size increases accordingly. For the ring without any ID, we have succeeded in reducing the coupling from 3.78% to 0.18% by reducing the closed orbit, especially the vertical orbit at the sextupole magnets, to nearly zero. However, after ID installation, such scheme could not reduce the coupling as it did earlier.

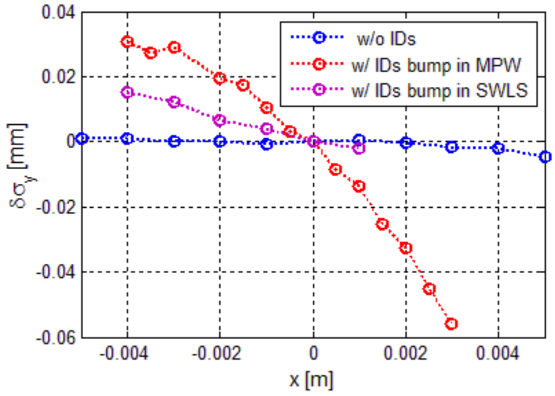

Figure 4: Vertical beam size change vs. horizontal orbit bumps in the MPW and SWLS.

Figure 4 shows the vertical beam size as a function of the beam horizontal position in both the MPW and the SWLS; it is smallest when the beam orbit is bumped to 3 mm in the MPW relative to the center. When electrons pass through an ID, they receive a vertical kick that depends on their horizontal position. This result confirms that the multipole field which results in coupling comes from the field error in the MPW.

To confirm that the coupling is caused by the MPW, the skew quadrupole field of the MPW is investigated as plotted in Fig. 5. We measure the skew quadrupole field by measuring vertical orbit shift as a function of horizontal orbit bump in the MPW, and compare this between when the MPW gap is opened and closed. The horizontal beam position outside the bump was kept fixed at the golden orbit. The bump at the MPW can only be in the range of -4 to 3 mm due to the limitation of the corrector magnet power supplies. At the center position of the IDs, the skew quadrupole field of the MPW is 799.80 G.cm while it is 342.44 G.cm for SWLS. The coupling can be reduced from 9.36% to 2.21% after the horizontal position in the MPW is bumped to +3 mm (toward ring center).

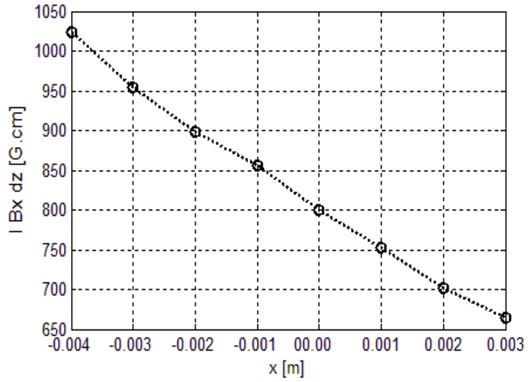

Figure 5: The skew quadrupole field generated by MPW.

CONCLUSION

The nonlinear effects of the two IDs were studied to better understand these magnets, and to improve the machine performance. The results from this study will be used to minimize the magnetic field errors from these magnets, and to compensate the resulting nonlinear effects on the beam.

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