Effects of Errors on the Dynamic Aperture of the Advanced Photon Source Storage Ring*

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Abstract

The individual tolerance limits for alignment errors and magnet fabrication errors in the 7-GeV Advanced Photon Source storage ring are determined by computer-simulated tracking. Limits are established for dipole strength and roll errors, quadrupole strength and alignment errors, sextupole strength and alignment errors, as well as higher order multipole strengths in dipole and quadrupole magnets. The effects of girder misalignments on the dynamic aperture are also studied. Computer simulations are obtained with the tracking program RACETRACK, with errors introduced from a user-defined Gaussian distribution, truncated at ±5 standard deviation units. For each error, the average and rms spread of the stable amplitudes are determined for ten distinct machines, defined as ten different seeds to the random distribution, and for five distinct initial directions of the tracking particle.

I. INTRODUCTION

In this paper, the results of a systematic and detailed study of alignment and fabrication error effects on the dynamic aperture of the Advanced Photon Source (APS) storage ring are presented.

The APS is a 7-GeV synchrotron radiation source. Its storage ring has a Chasman-Green type lattice, with a circumference of 1104 m, consisting of 40 cells, each containing one long zero-dispersion straight section. Figure 1 shows one section of the lattice, including the location of the beam position monitors and orbit-correcting magnets.

Magnet fabrication errors and alignment errors introduce distortions in the ideal orbit and cause a reduction of dynamic aperture, defined as the limiting stable betatron oscillation amplitude in either the horizontal or vertical plane of motion. Error fields in dipole magnets, roll angle misalignments and quadrupole displacements cause orbit distortions; quadrupole fields in dipole magnets, error field gradients in quadrupole magnets, and error quadrupole fields in sextupole magnets, cause detuning and changes in the betatron amplitude and dispersion functions. Dechromatizing effects can result from higher order error field gradients. Magnet misalignments included in this study were dipole and quadrupole rolls; quadrupole and sextupole displacements; and magnet support girder displacements. Magnet fabrication errors included dipole, quadrupole, sextupole, and higher order multipole field errors in dipole and quadrupole magnets. The effects of these errors on orbit functions, before and after correction of the closed orbit, are reported in Reference [1].

Careful analysis of the results led to the establishment of individual tolerance limits of acceptable error levels in the storage ring.

II. APERTURE REDUCTION

The dynamic aperture limits in presence of errors were obtained numerically using the tracking program RACETRACK [2] as modified by S. Kramer [3]. In the program, appropriate random errors can be introduced from a user-defined Gaussian distribution truncated at ±5 standard deviation units. A particle is considered stable if it tracks for 500 turns. Damping effects are not included.[1] For each case, 10 different "machines", corresponding to 10 different seeds to the random number generator, were constructed, and their rms average values calculated. The process was repeated for several error levels and for 5 different initial coordinates of the tracking particle, parametrized by $\Theta = \tan^{-1}(NY/NX)$, where NX and NY are the particle's oscillation amplitudes in the horizontal and vertical planes, respectively, expressed in units of the rms beam sizes σ_x and σ_y, at the center of the long straight section, where they assume the values 0.342 and 0.203 mm. The 5 initial directions were taken as those corresponding to Θ equal to 2°, 45°, 90°, 182° and 225°.

Roll angle misalignments of dipole magnets cause vertical orbit distortions. A roll angle of 1.0 mrad rms reduced the dynamic aperture by a factor of 2.

A quadrupole magnet displacement in either the horizontal or the vertical plane causes an error dipole field proportional to the product of the gradient field strength times the displacement. The large number and considerable strength of the quadrupole magnets together with the strong chromaticity correcting sextupoles make the APS storage ring very sensitive to quadrupole displacements. Indeed, of all the errors analyzed, these were the most restrictive: a horizontal displacement of 0.1 mm rms reduces the dynamic aperture by 53% (Θ = 45°). Increasing the error level to

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[1]The damping time for a positron in the APS storage ring corresponds to 2,600 turns; 500 turns correspond to a damping factor of $e^{(-500/2600)} = 0.83$.

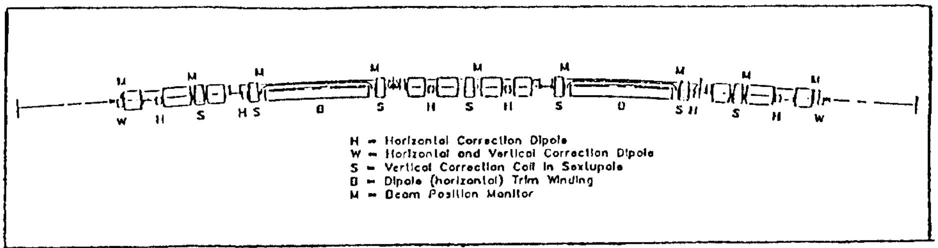

Figure 1. Layout of magnets for one cell of the APS storage ring.

1.5 mm further reduces the dynamic aperture by 20%, in addition to causing 2 unstable orbits out of the 10 processed. Horizontal and vertical displacements of 0.1 mm rms each, considered together, reduce the dynamic aperture by 70% and cause relatively large dispersion at the center of the long straight section [1]. The effect of the horizontal quadrupole displacements on the dynamic aperture can be seen in Fig. 2, for 4 levels of errors, where we included the dynamic aperture for the ideal lattice, for comparison, and the rms spread corresponding to 0.1 mm displacements. NX and NY denote, as aforementioned, the horizontal and vertical stable amplitudes in units of the rms beam sizes.

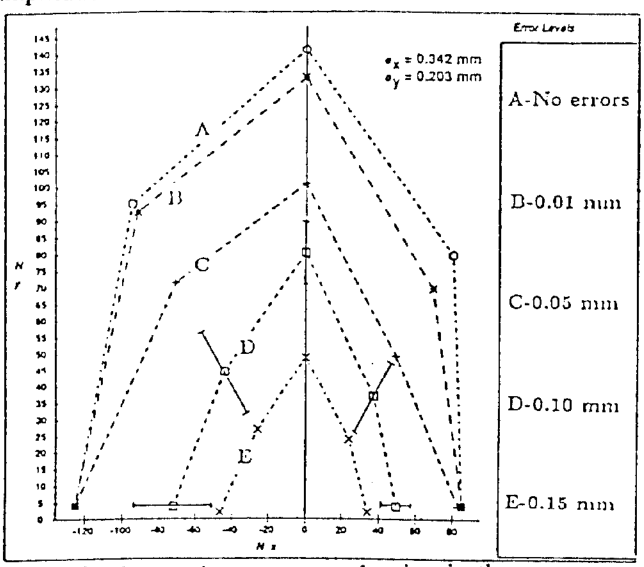

Figure 2. Dynamic aperture reduction in the presence of random horizontal quadrupole displacements, in units of the rms beam sizes σ_x and σ_y at the center of the straight section (see text).

Sextupole misalignments produced only small orbit distortions. Horizontal and vertical displacements of 0.2 mm rms, considered together, caused a 30% reduction of dynamic aperture.

The effects of error dipole fields in dipole magnets were found to be small, when compared to those of roll angle misalignments at the same error level (about one-third). For $\Delta B/B = 1 \times 10^{-3}$, there was a 17% reduction of dynamic aperture along the $\Theta = 45°$ direction.

Error field gradients in quadrupole magnets, $\Delta B'/B'$, induce detuning and distortions in the orbit functions. An off-set of 0.5% rms reduces the dynamic aperture by 56%.

In Fig. 3 we display the reduction of the dynamic aperture for various levels of random dipole roll angle misalignments, quadrupole and sextupole magnet displacements, dipole strength errors and quadrupole strength errors. Also included in the figure are misalignments of the magnet support system, considered individually and with quadrupole displacements of 0.1 mm superimposed. As can be seen in the figure, dipole field errors of 1×10^{-3} produce a much smaller reduction in the dynamic aperture than the reduction resulting from dipole roll errors at the same level. The lattice is not very sensitive to sextupole displacement errors. Also notice that magnet support misalignments are less restrictive than individual quadrupole misalignments by a factor of 5.

Error sextupole fields in sextupole magnets are responsible for changes in chromatization, and have little effect on the dynamic aperture; at a high error level of $\Delta B''/B'' = 2 \times 10^{-2}$ rms the reduction was 30% along the $\Theta = 45°$ direction.

We also analyzed the effects in the dynamic aperture due to systematic and random higher-order multipole field errors in dipole and quadrupole magnets. Random quadrupole field errors in dipole magnets, with multipole coefficient[2] $b_1 = 4 \times 10^{-4}$/cm produced a dynamic aperture reduction of 50%. In quadrupole magnets, the same level of reduction occurred for random normal sextupole field errors with $b_2 = 1 \times 10^{-3}/\mathrm{cm}^2$ and random octupole field errors with $b_3 = 3 \times 10^{-4}/\mathrm{cm}^3$. The effects of systematic sextupole and octupole field errors in quadrupole magnets, with, respectively, $b_2 = 2 \times 10^{-3}/\mathrm{cm}^2$ and $b_3 = 1 \times 10^{-3}/\mathrm{cm}^3$, can be seen in Fig. 4.

We have so far investigated the effects on the dynamic aperture for individual errors. The effects of combined errors are being investigated. Based on the criterion of an allowed 50% reduction of dynamic aperture, we have established *individual* tolerance limits for magnet errors in the APS storage ring. These limits are shown in Table 1.

III. CONCLUSIONS

The presence of strong sextupole magnets in the lattice cause the dynamic aperture to decrease sharply with orbit distortions.

The most restrictive effects are those resulting from quadrupole misalignments, leading us to impose a somewhat tight tolerance of 0.1 mm. A quadrupole misalignment of

[2]The multipole coefficients are defined by: $B = B_x + iB_y = B_o \Sigma_{n=o}^{\infty} (b_n + ia_n)(x + iy)^n$

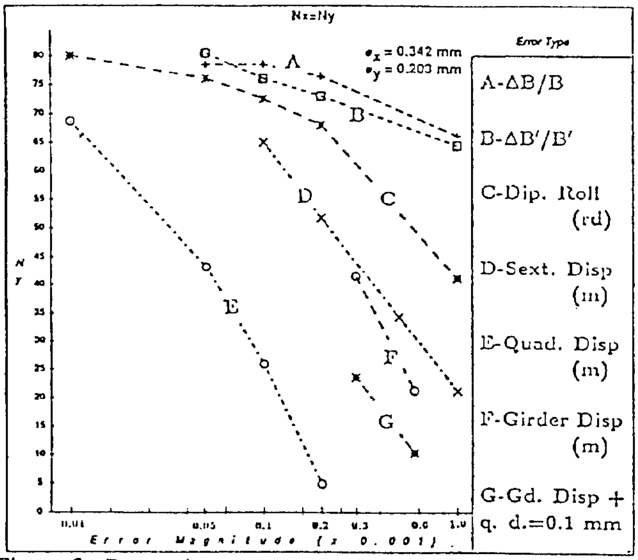

Figure 3. Dynamic aperture vs. error level for random dipole roll, quadrupole and sextupole magnet misalignments and displacements of the magnet support system, and dipole and quadrupole strength errors.

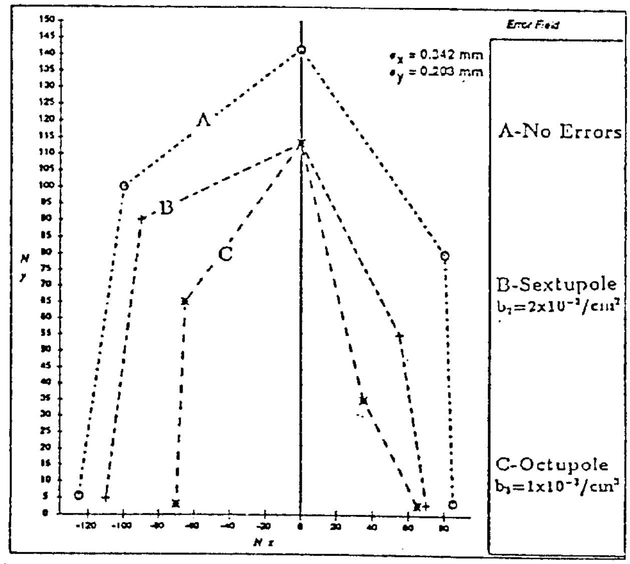

Figure 4. Effects of systematic sextupole and octupole field errors in quadrupole magnets, at the given multipole coefficients' levels.

Table 1

Error Type	Tolerance Limit	
Random roll angle misalignments of dipole magnets	1.0	mrad
Random horizontal or vertical displacements of quadrupole magnets	0.1	mm
Random horizontal or vertical displacements of sextupole magnets	0.2	mm
Random error dipole fields in dipole magnets	2×10^{-3}	
Random error field gradients in quadrupole magnets	4×10^{-3}	
Random error sextupole field gradients in sextupole magnets	2×10^{-2}	
Random normal quadrupole field errors in dipole magnets	$b_1 = 4 \times 10^{-4}$	cm^{-1}
Random normal sextupole field errors in dipole magnets	$b_2 = 3 \times 10^{-4}$	cm^{-2}
Random normal sextupole field errors in quadrupole magnets	$b_2 = 1 \times 10^{-3}$	cm^{-2}
Random normal octupole field errors in quadrupole magnets	$b_3 = 3 \times 10^{-4}$	cm^{-3}

0.1 mm produces orbit distortions of 5 mm at the sextupoles,[3] leading to a sizable detuning and consequent dynamic aperture reduction which is right at the tolerance limit. Within the tolerance, the closed orbit and beta and dispersion functions are acceptable [1]. Moreover, we showed that with groups of quadrupoles of alternating polarities aligned at high precision on girders, the alignment tolerance for the girders is greater than the tolerance for individual quadrupole misalignments by a factor of 5. This result is also predicted analytically [4]. Finally, as shown in [1], the designed correction dipole system effectively restores the dynamic aperture for transverse quadruple misalignments as large as 1mm rms.

IV. ACKNOWLEDGEMENTS

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[3]In the APS storage ring, this amplification factor, defined as the ratio of the rms quadrupole displacements and the rms orbit distortions, is of the order of 50.

V. REFERENCES

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