Effect of Magnet Sorting Using a Simple Resonance Cancellation Method on the RMS Orbit Distortion at the APS Injector Synchrotron*

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Abstract

The Advanced Photon Source injector synchrotron is a 7-GeV positron machine with a standard alternating gradient lattice. The calculated effect of dipole magnet strength errors on the orbit distortion, simulated by Monte Carlo, was reduced by sorting pairs of magnets having the closest simulated measured strengths to reduce the driving term of the integer resonance nearest the operating point. This method resulted in a factor of four average reduction in the rms orbit distortion when all 68 magnets were sorted at once. The simulated effect of magnet measurement experimental resolution was found to limit the actual improvement. The β-beat factors were similarly reduced by sorting the quadrupole magnets according to their gradients.

I. INTRODUCTION

The method for magnet sorting is based on the Floquet-Fourier decomposition of the orbit in the presence of error fields [1]. The expression for the orbit is:

$$\frac{x}{\sqrt{\beta}} = \sum_{k=-\infty}^{\infty} a_k \frac{\nu^2}{\nu^2 - k^2} \exp[i\,\phi\, k/\nu] \qquad (1)$$

where ϕ is the betatron phase, ν is the tune, and a_k is the coefficient given by:

$$a_k = \frac{1}{2\,\pi\,\rho\,\nu} \int_0^C ds\,\sqrt{\beta}\,\frac{\delta B}{B} \exp[-\,i\,\phi\,k\,/\,\nu] \qquad (2)$$

where δB is the measured field error in a dipole magnet, B is the field, and ρ is the radius of curvature.

Similar expressions exist for the β-beats where the coefficient is obtained by integrating over the gradient errors at twice integral multiples of the betatron phase. When all β are the same, as in the case for the APS synchrotron, the k^{th} coefficient is a vector sum in the complex plane of the field errors multiplied by the exponential factor in (2).

An analytic expression for the rms x orbit can be derived from the above expressions:

$$x_{rms}^2 = D \sum_k \frac{1}{(\nu^2 - k^2)^2} \left[\sum_i \left(\frac{\delta B}{B}\right)_i^2 + 2 \sum_i \sum_j \left(\frac{\delta B}{B}\right)_i \left(\frac{\delta B}{B}\right)_j \cos\left(\frac{(\phi_i - \phi_j)\,k}{\nu}\right) \right] \qquad (3)$$

where the i,j are pairs of magnets and D is a constant depending on ρ, ν, β and the magnet length. The sum on i and j is over the N magnets. The cosine terms of N/2 pairs of sorted magnets can be selected to cancel the first term while uncorrelated pairs of magnets will contribute zero on the average.

II. SORTING ALGORITHM AND SIMULATION

The lattice functions β and ϕ were generated by the standard transport code COMFORT. Figure 1 displays the horizontal phase as the polar angle, and the radial coordinate is β at the center of each dipole magnet. Dipole magnet sorting is accomplished by minimizing the coefficient of the k = 12 integer resonance for the APS synchrotron since the horizontal tune ν = 11.76.

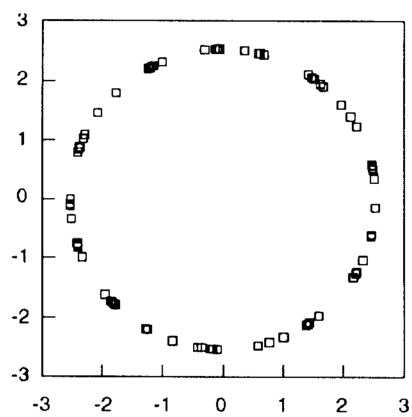

Figure 1. Dipole Phases

The large number of dipole lattice sites approximately 180 degrees apart in phase suggests the simplest algorithm. Magnets with the closest measured errors are assigned to lattice

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points with nearly opposite phase on the polar plot. The magnet errors were simulated by a Gaussian distribution as was the magnet measurement resolution.

III. RESULTS AND DISCUSSION

A. Dipoles

The comparison of the random assignment of dipoles with the sorted case of all 68 magnets, assuming zero magnet measurement experimental error, is shown in Figure 2. The mean reduction in rms x orbit is a factor of approximately four and agrees with (3). The random selection case also exhibits a long tail of upward fluctuations.

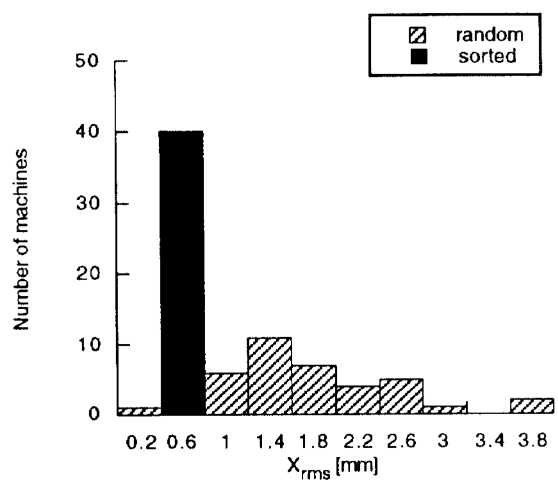

Figure 2. Random vs sorted orbits for 40 machines

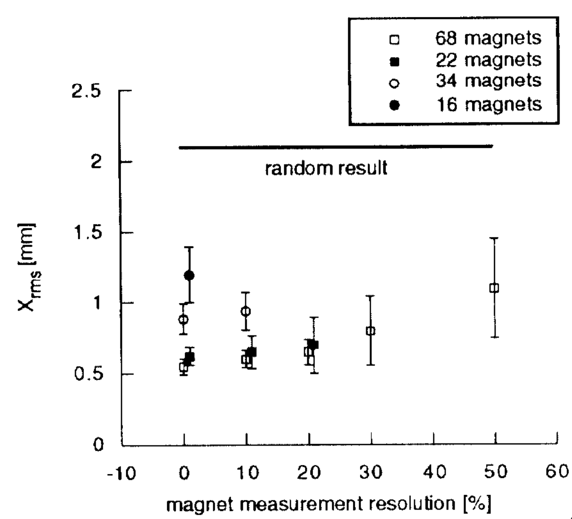

Figure 3. Magnet sorting result for $\Delta B/B = 10^{-3}$

Identical random field errors were used for both cases. The k=1,2,3 coefficients have the largest contribution to the orbit after sorting. Figure 3 shows the mean rms orbit for different numbers of dipoles sorted at once. The case of N=22, one third of the ring, is better than the case of 34 magnets because of reduction of the k=2,3 coefficients due to the periodicity of the lattice. The experimental magnet measurement resolution does not dramatically affect the results for resolution of up to 10% of the rms of $\delta B/B$. In comparison, the tolerance specified on the rms $\delta B/B$ is 10^{-3} and the estimated measurement resolution [2, 3] of the APS synchrotron dipole measurement system is 10^{-4}.

B. Quadrupoles

The sorted results for the rms β-beat factors are reduced by a factor of six over the unsorted results. The 40 focusing and 40 defocusing quadrupoles are sorted separately according to their gradients. The difference in sorting improvement compared to the dipoles is primarily due to the properties of the lattice resulting in sites with better cancellation. In the case of the quadrupoles, the best result was obtained by assigning pairs of magnets with opposite gradient errors to the same value of twice the phase on a polar plot. The cancellation using sites with twice the phase appoximately 180 degrees apart was not as effective and resulted in a factor of 3.5 average improvement in the beat factor.

IV. CONCLUSIONS

A simple method for sorting magnets that relies on basic theory yields reduction factors of 4 in orbit for the dipoles and 6 in beat factors for quadrupoles at the APS synchrotron. Similar reductions can be obtained without having the entire sample of magnets to choose from. Analytical estimates and Monte Carlo methods yield the same average results. This procedure can be used to gain an added margin for safety in magnet manufacture. The reductions in x_{rms} obtained from sorting using a more sophisticated method would be limited by the magnet measurement resolution unless the ratio of rms measurement error to rms field error were smaller than 10%.

V. REFERENCES

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