ANL/ASD/CP--85027
Conf-950512--161

Effects of Imperfections on the Dynamic Aperture and Closed Orbit of the IPNS Upgrade Synchrotron*

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Abstract

Magnet imperfections and misalignments are analyzed in terms of their effects on the dynamic aperture and closed orbit of the IPNS Upgrade synchrotron. The dynamic aperture is limited primarily by the presence of chromaticity-correcting sextupoles. With the sextupoles energized to the values required to adjust the chromaticities to zero, further reductions of the dynamic aperture caused by dipole strength and roll errors, quadrupole strength and alignment errors, and higher-order multipole errors are studied by tracking. Design specifications for the dipole corrector magnets are obtained and the dynamic aperture is studied before and after correction of the closed orbit. The use of harmonic-correcting sextupoles to reduce the amplitude-dependent tune shifts driven by the chromaticity-correcting sextupoles is investigated.

I. INTRODUCTION

The proposed IPNS Upgrade is a dedicated source for neutron scattering experiments that uses a rapid-cycling synchrotron (RCS) to accelerate 1.04^{14} protons per pulse from 400 MeV to 2 GeV. A summary description of the machine is given elsewhere in these proceedings [1]. The RCS lattice is 190.4 m long and contains four superperiods. Each superperiod consists of three FODO cells of about 90° advance in each transverse plane, two dispersion-suppressor cells, and two dispersion-free straight cells. The orbit functions for one superperiod are shown in Figure 1, which has mirror symmetry at both ends.

The key design feature of the RCS is the prevention of beam losses during the injection, capture, and acceleration processes. Beam loss prevention in the transverse phase space is achieved by providing large dynamic aperture in both transverse planes. We have performed tracking studies to ensure that the RCS has a dynamic aperture larger than the physical aperture of the vacuum chamber, taking into account magnetic field imperfections due to fabrication tolerances and misalignments caused by surveying tolerances. In this paper, we present the results of tracking studies of closed-orbit distortions and dynamic aperture reduction in the RCS.

II. CLOSED-ORBIT DISTORTIONS

We investigated closed-orbit distortions (COD) caused by quadrupole misalignments, $(\delta z)_Q$, field deviations in dipole magnets, $(\delta B/B)_B$, and dipole roll angle misalignments, $(\delta\theta)_B$. The nominal tolerance values for these

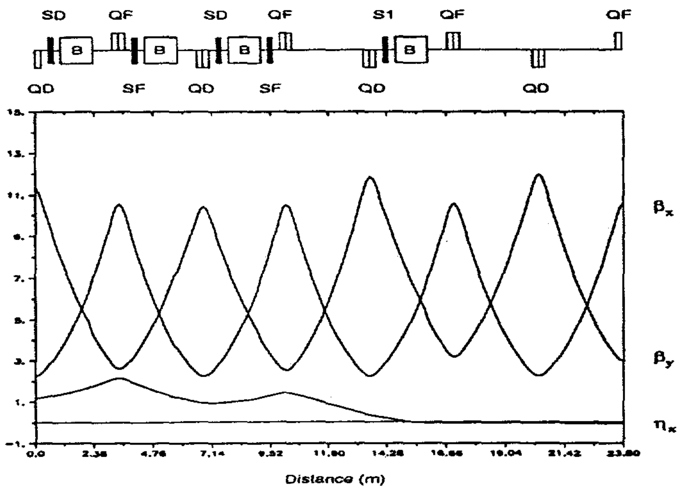

Figure 1
Lattice Functions for One-Half of a Superperiod.

quantities were estimated based on the actual measured data from the 7-GeV Advanced Photon Source (APS) booster synchrotron [2], and are shown in Table 1. In the table, $(\delta z)_Q$ denotes quadrupole misalignments in either the $x-$ or $y-$ plane.

Table 1
Nominal Alignment and Field Quality Tolerances

$(\delta z)_Q$	$(\delta B/B)_B$	$(\delta\theta)_B$
0.2 mm rms	0.1% rms	1 mrad rms

The analytically derived amplification factors for quadrupole misalignments in the RCS lattice are:

$$A_x = (\Delta x)_{max}/(\delta x)_Q = 33,\ A_y = (\Delta y)_{max}/(\delta y)_Q = 24,$$

where $(\Delta z)_{max}$ is the maximum COD in the horizontal or vertical direction, $(\Delta z)_{max} = 2(\Delta z)_{rms}$, and a Gaussian distribution is assumed.

The amplification factors for field deviations in dipole magnets are:

$$A_x = \frac{(\Delta x)_{max}}{(\delta B/B)_B} = 19\ m,\ A_y = \frac{(\Delta y)_{max}}{(\delta B/B)_B} = 12\ m,$$

where orbit distortions in the vertical direction are caused by dipole roll angle misalignments.

Using these amplification factors, the estimated maximum orbit distortions are $(\Delta x)_{max} = 18\ mm$ and $(\Delta y)_{max} = 14\ mm$. An effective scheme to reduce the orbit distortions is therefore needed.

The orbit corrections were simulated by using the program MAD [3]. Since the number of simulations is finite,

*Work supported by U.S. Department of Energy, Office of Basic Energy Sciences under Contract No. W-31-109-ENG-38.

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we used relaxed tolerances of $(\delta z)_Q = 0.4\ mm$ rms to cover the worst cases and increase the level of confidence on the results. The corresponding specification of the required corrector strengths is conservative.

The simulations were carried over 30 different machines. In the RCS, horizontal and vertical beam position monitors (BPMs) are located in the focusing and defocusing quadrupoles, respectively. Similarly, horizontal and vertical correctors are located near the focusing and defosusing quadrupoles. There are a total of 28 BPMs and 28 correctors in each plane. Horizontal and vertical correctors of up 85 and 71 G-m, respectively, permit correction of the orbit to within the rms BPM accuracy of 0.1 mm. The maximum dipole corrector strength is specified as 110 G-m. The engineering design for corrector magnets with an effective length of 15 cm is detailed in [4].

III. DYNAMIC APERTURE

The dynamic aperture in the RCS is limited primarily by the presence of chromaticity-correcting sextupoles. The natural normalized chromaticities of the lattice are $\xi_x = -1.06$ and $\xi_y = -1.20$. Chromaticity is adjusted by 16 horizontal focusing and 16 horizontal defocusing sextupoles. With the sextupoles energized to the values required to adjust the chromaticities to zero, we investigated further reductions of the dynamic aperture caused by random misalignments and magnet fabrication imperfections. Dynamic aperture limitations were simulated by using the symplectic kick code RACETRACK [5].

The dynamic aperture was defined as the limiting stable betatron amplitude of a particle that survived 2,000 turns in a static field. This corresponds to about two synchrotron periods at injection. Tests carried out up to 10,000 turns showed very little difference from the results obtained with 2,000 turns. The distribution of errors was assumed to be Gaussian, with a cutoff of $\pm 5\sigma$, and the simulations were performed for 10 different machines.

Dynamic aperture reductions caused by closed-orbit distortions, arising from the alignment tolerances discussed in the previous section, with and without closed-orbit corrections, are shown in Figure 2. The lines in the figure are the averages and the error bars are the standard deviations for the 10 machines.The dynamic apertures are displayed at the focusing quadrupole. The dynamic aperture of the perfect machine and the beam-stay-clear region (BSC), defined as $\sqrt{\frac{2\varepsilon\beta}{\pi}} + \frac{\eta}{\delta p/p} + COD$, where η is the dispersion function, ε is the emittance, and $\delta p/p$ is the momentum deviation, are also shown. The closed-orbit was corrected to 0.1 mm rms, as described in Section II. Before orbit correction, the dynamic aperture is still sufficient to permit beam injection. Correction of the orbit restores the dynamic aperture to that of the perfect machine.

Dynamic aperture reductions due to magnetic field imperfections were studied by using the multipole coefficients a_n and b_n, shown in Table 2. The coefficient values were obtained by scaling the measured data of the APS booster synchrotron magnets to the RCS magnets. The magnetic field expressed in terms of these coefficients is:

$$B = B_0 \sum_{n=0}^{\infty} (b_n + i a_n)(x + iy)^n, \qquad (1)$$

where a_n and b_n are the normal and skew coefficients in units of cm^{-n}.

Table 2
Multipole Coefficients of RCS Magnets

Multipole*	Random cm^{-n}	Systematic cm^{-n}
b_{1D}	2.60E-6	-7.10E-6
b_{2D}	3.90E-8	-0.70E-6
b_{1Q}	4.90E-4	2.50E-4
a_{1Q}	1.70E-4	-0.40E-4
b_{2Q}	4.80E-6	-1.20E-6
a_{2Q}	0.13E-4	0.28E-6
b_{3Q}	1.20E-6	-5.50E-6
a_{3Q}	0.62E-6	0.22E-6
b_{4Q}	3.60E-8	0.30E-8
a_{4Q}	4.50E-8	-0.80E-8
b_{5Q}	0.24E-8	1.95E-8
b_{2S}	1.36E-3	5.00E-4
a_{2S}	3.30E-4	-4.90E-4
b_{3S}	0.17E-4	-2.40E-6
a_{3S}	0.61E-4	3.20E-6
* D = dipole	Q = quadrupole	S = sextupole

There were no appreciable effects on the dynamic aperture for multipoles up to twice the values depicted in Table 2. A reduction of 15% was observed for multipoles at four time those values.

Finally, misalignments were included along with multipole components. Reductions, both before and after closed-orbit corrections, were studied. The results are shown in Figure 3. The dynamic aperture before COD corrections is still as large as the BSC, thus permitting the establishment of a closed-orbit solution at injection. The dynamic aperture after correction is very close to that obtained for multipole components only, as expected.

IV. HARMONIC CORRECTION

The tunes of the bare lattice are $\nu_x = 6.821$ and $\nu_y = 5.731$. However, the tune shift due to space charge forces moves the working point to the proximity of the $3\nu_x = 20$ resonance line [4]. This resonance can be driven by the the chromaticity-correcting sextupoles and can have a deleterious effect on the circulating beam. The 20^{th} harmonic of the sextupole component is suppressed by placing harmonic-correcting sextupoles (denoted by S1 in

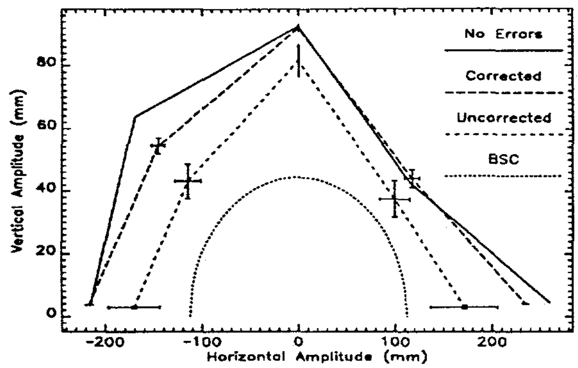

Figure 2
Dynamic Aperture in the Presence of Quadrupole Misalignments, Dipole Field Deviations and Dipole Roll Angle Misalignments. (The dynamic aperture for the perfect machine is shown for comparison. The ellipse represents the BSC region at the focusing quadrupole.)

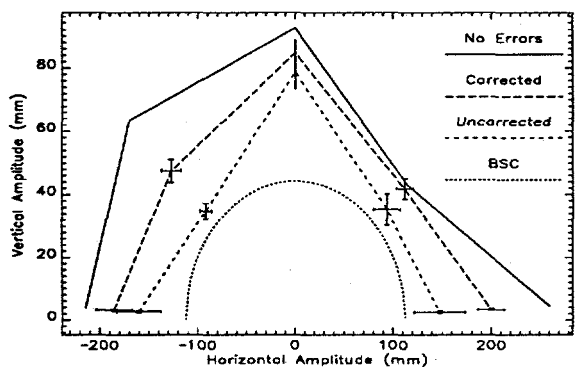

Figure 3
Dynamic Aperture Reductions Caused by Misalignments and Multipoles, Plotted before and after Corrections of the Closed Orbit.

Figure 1) in the dispersion-free sections. Horizontally defocusing sextupoles with integrated strength of $0.4m^{-2}$, placed in the eight dispersion-suppressor cells, eliminate the 20^{th} harmonic. The phase spaces with and without harmonic-correcting sextupoles are shown in Figure 4. The dynamic apertures with and without harmonic-correcting sextupoles are shown in Figure 5.

V. Conclusion

Linear and nonlinear effects on the lattice of the IPNS Upgrade RCS were studied in terms of the closed orbit, dynamic aperture, and harmonic-correction techniques. The simulations showed that the closed orbit distortions can be corrected within the desired accuracy, and the dynamic aperture is large enough to contain the beam-stay-clear region. Harmonic-correcting sextupoles, properly placed in the lattice, can effectively remove the dangerous resonance line $3\nu_x = 20$ driven by the chromaticity-correcting sextupoles, without degrading the dynamic aperture.

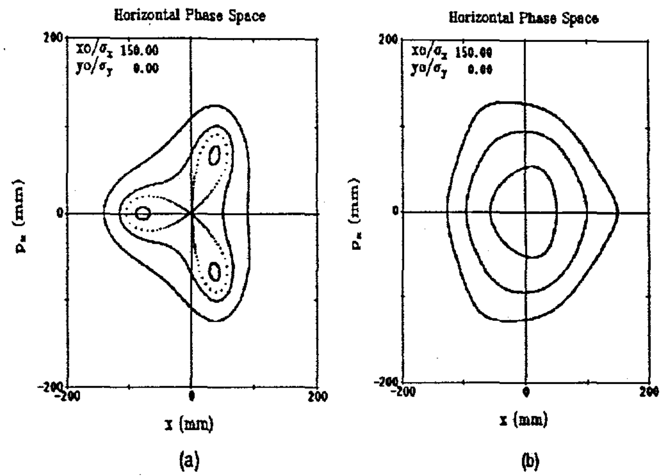

Figure 4
Horizontal Phase Space Motion with $\nu_x = 6\frac{2}{3}$ without (a) and with (b) Harmonic-Correcting Sextupoles.

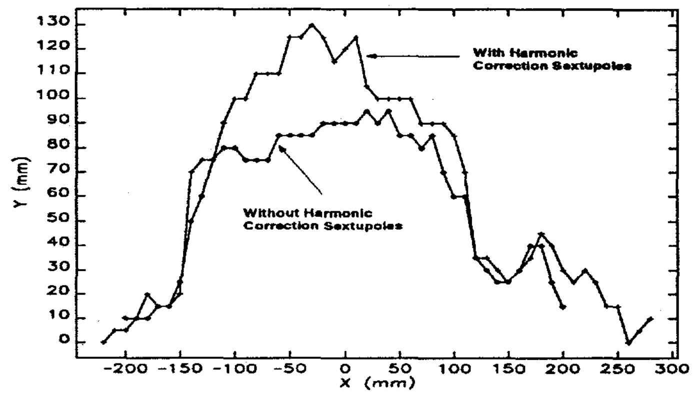

Figure 5
Dynamic Apertures with and without Harmonic-Correcting Sextupoles.

VI. References

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