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EVALUATION OF POWER SUPPLY AND ALIGNMENT TOLERANCES FOR THE ADVANCED PHOTONS SOURCE UPGRADE*

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Abstract

A hybrid seven-bend-achromat lattice that features very strong focusing elements and provides an electron beam with very low emittance has been proposed for the Advanced Photon Source upgrade [1, 2]. In order to be able to maintain stable operation, tight tolerances are required for various types of errors. Here we describe an evaluation of the effects of various errors, including magnet power supplies, alignment, and vibration.

STATIC RANDOM ERRORS

Examples of static errors are power supply calibration errors, alignment errors, etc. The effect of these errors in most cases can be measured and corrected. Two types of static errors are distinguished: initial errors (errors expected during commissioning) and reproducibility errors (errors after turning power supplies off and then back on). Table 1 gives goals for various machine parameters.

Table 1: Goals for Initial Errors and Reproducibility in High-Level Machine Parameters Driven by Static Errors

	Initial error	Reproducibility
Energy	10^{-3}	10^{-4}
Orbit	2 mm	0.1 mm
Betatron tune	0.1	0.01
Beta functions	20%	2%
Chromaticity	1 unit	0.1 unit

When a dipole power supply current changes, the energy and orbit of the electron beam change. To calculate the sensitivity of the energy offset to such errors, an `elegant` [3] simulation was used. 200 sets of dipole fractional errors with 10^{-5} rms were generated, then the orbit was calculated and corrected. Two different orbit correction configurations were tested. The results are shown in Fig. 1, left. The distribution width varies by about a factor of two, so the energy error depends little on whether orbit correction is running or not. The amplifying effect of powering dipoles in series on the energy error is significant, as Fig. 1 (right) shows. The resulting allowable initial dipole errors are $2 \cdot 10^{-3}$. Initial orbit distortion is generated by dipole errors and quadrupole misalignments, while orbit errors after a shutdown result from dipole and corrector reproducibility errors. The orbit requirements in Table 1 were chosen to ensure that the initial orbit fits inside the vacuum chamber. This leads to unrealistic requirements for individual quadrupole alignment of 10 µm. To relax this requirement, a single-turn trajectory

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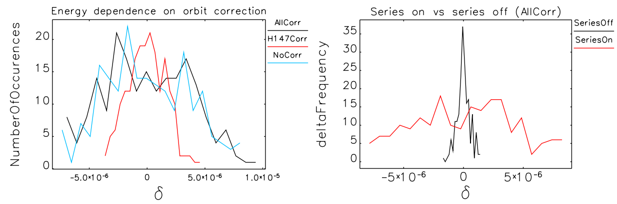

Figure 1: Left: Distribution of Energy Errors for Two Different Orbit Correction Configurations (Black and Red) and without Orbit Correction (Blue). Right: Comparison of Energy Errors for the Cases When M1 and M2 Dipoles Powered in Series or Separately.

correction will be used to obtain the first closed orbit. For orbit reproducibility after shutdowns, all of the error budget is assigned to dipoles and correctors. This gives $\Delta\alpha/\alpha = 10^{-4}$ for dipoles and $\Delta\theta/\theta = 7 \cdot 10^{-3}$ for correctors, assuming an equally split error budget.

Betatron tune errors come from quadrupole gradients, beam energy, and orbit inside sextupoles. Initial tune errors will be dominated by the orbit in sextupoles. Simple estimations show that 1-mm rms orbit errors in sextupoles will produce a tune error of 0.9. Therefore, during commissioning, after the first closed orbit has been established, the tune will need to be corrected. Despite this need for early tune correction, it is still advisable to limit tune error contributions from quadrupoles and dipoles. The effect of quadrupole errors can be estimated using a simple expression, while the effect of dipole errors is more complex and was obtained from simulations. Assuming that the tune error budget of 0.1 is distributed equally between quadrupoles and dipoles, the requirements for the initial errors are: $\Delta K_1/K_1 = 3 \cdot 10^{-3}$ and $\Delta\alpha/\alpha = 1.2 \cdot 10^{-3}$.

Initial beta function errors are expected to be dominated by the orbit errors in sextupoles. If the quadrupole contribution is limited to 20% beta beating, a simple simulation of beta function errors due to random quadrupole errors results in an initial quadrupole error requirement of $1 \cdot 10^{-3}$.

Chromaticity errors are generated by sextupole errors and by lattice errors. Simulations show that chromaticity errors after the beam is first stored have an rms of five units due to lattice errors. After orbit correction, the chromaticity error decreases to one unit rms. The contribution from sextupole strength errors is required to be one unit as well. Simple calculation results in the initial error requirement of $2.7 \cdot 10^{-2}$. Table 2 summarizes tolerances for random static errors.

VARIABLE ERRORS

Variable errors can be split in several parts according to their frequency spectrum: "slow" (slower than 100 seconds), "fast" (between 0.01 Hz and 1 kHz), and "very fast" (faster than 1 kHz). The required limits on the varying errors are

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Table 2: Summary of Static Error Tolerances. Alignment tolerances are discussed in [4].

	Initial error	Reproducibility
Dipole strength	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{-4}$
Quadrupole strength	$1 \cdot 10^{-3}$	$1 \cdot 10^{-4}$
Sextupole strength	$2.7 \cdot 10^{-2}$	$2.7 \cdot 10^{-3}$
Corrector strength		$1 \cdot 10^{-2}$

given in Table 3. Tolerances for 0.01 Hz – 1 kHz bandwidth are described in what follows.

Table 3: Limits on Varying Errors

	Range	Limit (rms)
Orbit stability	>1 kHz	0.4 σ
	0.01 Hz – 1 kHz	0.1 σ
	<0.01 Hz	1 μm
Tune stability	0.01 Hz – 1 kHz	10^{-3}
	<0.01 Hz	10^{-3}

Orbit Motion

Orbit motion is mainly produced by the electrical noise of the magnet power supplies and by vibration of the magnets. Since orbit correction is always running during user operation, BPM vibration can also lead to orbit motion. Electrical noise and magnet vibration affect the orbit according to frequency-independent amplification factors F of the corresponding magnets. Electrical noise is attenuated by the solid cores of the magnets and vacuum chamber. The orbit motion is reduced by the orbit correction with a frequency-dependent attenuation factor A. In addition, BPM vibration results in orbit motion that follows BPM position exactly when orbit correction is running and assuming that orbit correction corrects BPM errors exactly to zero. If each component is responsible for a fraction P of the square of the beam motion, then the total motion can be written as

$$\begin{aligned} q^2_{\text{total}} &= q^2_{\text{v}} + q^2_{\text{e}} + q^2_{\text{BPM}} \\ &= P_{\text{v}}\, P_{\text{girder}}\, q^2_{\text{total}} + P_{\text{v}}\, P_{\text{magnet}}\, q^2_{\text{total}} + \\ &\quad P_{\text{e}}\, P_{\text{corr}}\, q^2_{\text{total}} + P_{\text{e}}\, P_{\text{dip}}\, q^2_{\text{total}} + P_{\text{BPM}}\, q^2_{\text{total}} \\ &= \left(u_{\text{girder}}\, F_{\text{girder}}\, A_{\text{v}}\right)^2 + \left(u_{\text{magnet}}\, F_{\text{magnet}}\, A_{\text{v}}\right)^2 + \\ &\quad (u_{\text{corr}}\, F_{\text{corr}}\, A_{\text{e}})^2 + \left(u_{\text{dip}}\, F_{\text{dip}}\, A_{\text{e}}\right)^2 + u^2_{\text{BPM}}\,, \end{aligned} \tag{1}$$

where v and e stand for vibrational and electrical, and q stands for x or y. Vibrational motion is split into girder P_{girder} and separate magnets P_{magnet} contributions, while electrical noise motion is split into contributions from dipoles P_{dip} and correctors P_{corr}. Also, u_{girder} and u_{magnet} are the girder and magnet motion, u_{corr} and u_{dip} are electrical noise in correctors and dipoles, F_{girder}, F_{magnet}, F_{corr}, and F_{dip} are motion amplification factors, u_{BPM} is BPM motion, and A_{v} and A_{e} are orbit attenuation factors of vibrational and electrical motion. Specific assumptions about noise and orbit correction are the following: (1) Electrical noise has power spectral density (PSD) with $1/f$ dependence on frequency and extends in both directions without limit. (2) Vibrational noise of the girders follows the motion of the floor and has $1/f^3$ PSD dependence [5]. The motion has been limited to frequencies above 0.1 Hz, corresponding to correlated motion over scales longer than one sector. (3) Vibrational motion of the magnets on the girders follows the same spectrum as the girder motion, but the motion of different magnets on the girder is uncorrelated. (4) BPM motion has the same spectrum and magnitude as the girder motion (or $g_{\text{girder}} = g_{\text{BPM}}$). (5) Orbit correction is an integral controller with PSD dependence of f^2 and a bandwidth of f_{bw}. (6) Since preliminary measurements show that the total noise contribution of spectral lines to total noise does not exceed 50%, these are neglected.

Some of the assumptions are summarized in Fig. 2. The resulting PSD of the beam motion is the product of the three functions shown in the schematic. The multiplication and integration of the resulting PSD were done numerically. Orbit correction attenuation factors A were calculated as square roots of the ratios of initial PSD to PSD after correction. Specific assumptions about budgeting and bandwidths that were used in the calculations are given in Tables 4 and 5. The final tolerances are given in Table 6.

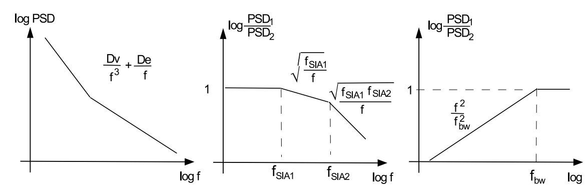

Figure 2: From left to right: Power Spectral Density of Electrical and Vibrational Noise with Amplitudes D_{e} and D_{v}; electrical noise attenuation due to solid iron core and vacuum chamber with bandwidths f_{SIA1} and f_{SIA2}; beam motion attenuation due to orbit correction with bandwidth f_{bw}.

Table 4: Assumptions on Characteristic Frequencies Used in Calculation of the Orbit-motion-related Tolerances and Resulting Orbit Correction Attenuation Factors.

Orbit correction bandwidth	f_{bw}	1 kHz
Lower frequency of interest	f_1	0.01 Hz
Upper frequency of interest	f_2	1 kHz
Lower band of vibrational motion	f_{v}	0.1 Hz
Vibr. noise attenuation (0.1-1000 Hz)	A_{v}	1/2300
El. noise attenuation (0.01-1000 Hz)	A_{e}	1/34

Orbit Motion without Orbit Correction

During machine studies, some measurements—e.g., response matrix measurement—are performed without orbit correction. Thus, orbit motion noise must not be excessive even without orbit correction. From present experience, a requirement of 1 μm seems reasonable. In this case, there will be no attenuation due to orbit correction. However, there

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Table 5: Total and Fractional Orbit Motion Budget. First data column is for the case with orbit correction running, the second column is for studies when orbit correction is off. Top part of the table gives the overall budget breakdown, middle part gives the vibrational part breakdown, and bottom part gives the breakdown of the electrical part.

Total motion budget	P_{total}	0.1σ	1 µm
Power supply noise	P_e	0.1	0.89
BPM motion/noise	P_{BPM}	0.89	0.01
Vibrational noise	P_v	0.01	0.1
Vibrational due to girders	$P_{v\,girder}$	0.5	0.5
Vibrational due to quads	$P_{v\,quad}$	0.5	0.5
Electrical due to correctors (X)	P_{corr}	0.7	0.3
Electrical due to correctors (Y)	P_{corr}	1.0	1.0
Electrical due to dipoles (X)	P_{dip}	0.3	0.7

Table 6: Orbit-motion-based Tolerances for Dipole and Corrector Noise and for Vibration. Cases with and without orbit correction (OC) are presented.

	With OC		Without OC	
	X	Y	X	Y
u_{girder} (µmm)	1.70	0.40	0.32	0.56
u_{quad} (µm)			0.13	0.09
$(\delta I/I_{max})_{cor} \cdot 10^4$	4	2	1.9	2.5
$(\delta\varphi/\varphi)_{dipM3M4} \cdot 10^5$	3	—	2.2	—
$(\delta\varphi/\varphi)_{dipM1M2} \cdot 10^5$	4.5	—	3.1	—

will be attenuation due to measurement averaging. The total beam motion can be written as in Eq. 1, but without attenuation due to orbit correction and with A_{aver} attenuation of the overall motion due to averaging.

In addition, if a single orbit measurement is done on a one-second scale, only motion above 1 Hz contributes to the measurement noise, while the motion below 1 Hz gets partially eliminated when two subsequent orbit measurements are subtracted from each other. This limits the frequency range of interest to 1 Hz and up. To make the numbers in this section consistent with the 0.01-1000 Hz bandwidth used above, the frequency dependence of the respective PSDs is used to extrapolate the requirements. Table 6 shows results of calculations that take the extrapolation factors into account. The apportioning of the motion budget is given in Table 5, second column.

Tune Variation

The main sources of tune variation are quadrupole and dipole power supply noise and orbit noise in sextupoles. It is assumed that no tune correction is running in this bandwidth. The effect of the quadrupole and dipole errors can be calculated the same way it was done for the static errors above. Another possible source of tune variation is sextupole power supply noise. This effect was estimated assuming independent orbit errors in sextupoles with rms of 100 µm and using the expression for the tune change due to focusing errors.

An important effect on tune stability comes from orbit noise in sextupoles. The sextupoles are located in triplets with very small phase advance across the each triplet, therefore the orbit in sextupoles of one triplet cannot be considered independent. The orbit in different triplets can be assumed independent because they are separated in phase and could have orbit correctors between them. Using these assumptions, we get the tune variation due to allowable orbit motion of $6 \cdot 10^{-4}$ in both planes. The final tolerances based on tune requirements are shown in Table 7.

The overall tolerances are summarized in Tables 8 and 9.

Table 7: Betatron Tune-based Tolerances for Power Supply Noise

Source	Allocation	Tolerance
Quadrupoles	0.18	$2.3 \cdot 10^{-5}$
Dipoles M1 and M2	0.4	$1.4 \cdot 10^{-5}$
Dipoles M3 and M4	0.05	$5.3 \cdot 10^{-5}$
Sextupoles	0.01	$1.8 \cdot 10^{-3}$
Orbit motion	0.36	

Table 8: Summary of Rms Electrical Noise Tolerances for 0.01-1000 Hz Bandwidth

Magnet type	Requirement	Based on
Correctors	$1.9 \cdot 10^{-4}$	Orbit stability w/o OC
Dipoles M3-M4	$2.2 \cdot 10^{-5}$	Orbit stability w/o OC
Dipoles M1-M2	$1.4 \cdot 10^{-5}$	Tune stability
Quadrupoles	$2.3 \cdot 10^{-5}$	Tune stability
Sextupoles	$1.8 \cdot 10^{-3}$	Tune stability

Table 9: Summary of Vibrational Tolerances. Two bandwidths are given. The numbers in this table are the most demanding requirements based on either stability requirement with or without orbit correction.

	X (rms)	Y (rms)	X (rms)	Y (rms)
	1-100 Hz		0.1-1000 Hz	
u_{girder}	32 nm	40 nm	320 nm	400 nm
u_{quad}	13 nm	9 nm	130 nm	90 nm

CONCLUSIONS

An extensive tolerance study for the APS Upgrade lattice shows that the tolerances are challenging but achievable.

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