NEW CONSIDERATION FOR INSERTION-DEVICE DIPOLE-ERROR PERTURBATION REQUIREMENTS WHEN INCLUDING THE EFFECTS OF ORBIT FEEDBACK*

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Abstract

For various reasons insertion devices (IDs) in storage ring light sources generally produce small dipole perturbations on the stored beam, which is usually compensated by orbit correction. Tougher orbit stability requirements for the Advanced Photon Source Upgrade (APS-U) project have led us to revisit the requirements of these magnetic-field errors. When including the effect of orbit correction (slow orbit feedback plus fast orbit feedback), we realized that the field-error requirements change from a limit in absolute values of magnetic-field error integrals to that of *rates of change* in magnetic-field error integrals. Some modeling of the combined effect of ramping the strength of an ID with orbit correction will be presented. This new thinking has the potential of greatly alleviating the tuning requirements of insertion devices of all types.

INTRODUCTION

In the early stages of APS operation, perturbations from insertion device (ID) field errors was studied intensively, resulting in a set of ID field specifications [1]. Since then, many IDs have been built, measured, and placed into operation at APS. Their properties and the achievable manufacturing limits are by now well known.

The first- and second-field integrals of an ID are not zero, and also, very importantly, vary with gap. To maintain the source-point during user operations, these perturbations must be held within some limits relative to an appropriate short-term "average reference" condition, which is not necessarily the same as the open-gap condition or starting conditions.

The undulators are slow-moving devices; the induced perturbation on the stored beam has a time scale of 1 seconds to 2 to 3 minutes. When a device gap is scanned repeatedly near their closed position, the period could be a few seconds to a few minutes, depending on the experimenter's data collection requirements. At the smallest gap position a significant beam perturbation could take place within 1 second. Thus the frequency range of interest is, say, 0.01 to 1 Hz, the lower limit selected to be approximately the reciprocal of two minutes.

Given that the stored beam can be subjected to perturbations from general sources of all frequencies, a general beam stability requirement for APS-U was recently reestablished (see Table 1). Just like the original APS beam stability requirement, this requirement is meant as a guide for setting limits on individual sources of perturbation. One of the specifications sets limits on all sources in the frequency range 0.01 to 200 Hz (middle column in Table 1).

As discussed previously, conventional undulators are expected to produce perturbations within a tiny fraction of that frequency range, while other sources produce perturbations over the whole frequency range. Thus some of the orbit motion spectrum integrals of Table 1 must be allocated to undulator perturbation limits. In other words, if 3 μm is the maximum allowable rms orbit motion in the x plane from all sources, then a smaller number, say, 1.0 μm, would have to be taken as the maximum allowable rms motion in the 0.01-1 Hz range for undulators.

NEW ALLEVIATING FACTORS

Restricting ID source perturbations to a small amount like 1 μm may seem impossible at first. However, there are many alleviating factors not considered until now and some complicating factors used for years that are no longer needed:

Previously it was assumed that ID gaps could be moving together. Actually, independently operated gaps rarely move together. This will remove a factor $\sqrt{N_{\rm ID}}$ due to the number of IDs.

If there are independent IDs whose gaps are scanned slowly for long periods, the perturbation frequency will be below the band (below 0.01 Hz), in which case orbit correction cancels the perturbation with very high (virtually "infinite") gain.

Two orbit correction systems are running full-time in different frequency bands and have particularly high gain (i.e., correction effectiveness) in the 0.01 - 1 Hz frequency range of interest. A high gain allows larger tolerances for ID perturbation. Figure 1 shows the gain of the orbit correction as presently configured.

ID gap feedforward on nearby storage ring dipole correctors can be used to reduce the effort from the feedback correctors by 90% in DC mode. However, we found that the EPICS network for communicating gap information is much slower than the dedicated reflective memory of the orbit feedback system. Thus a feedforward system for correcting the orbit perturbation would not be needed to improve stability.

The ID perturbation when the gap is moving is not really a sequence of steps but rather segments of ramp errors of

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Table 1: Main Lattice Parameters and Beam Stability Requirements in rms and in Integrated Power Spectral Density in the 0.01 - 200 Hz Band

	Original specification	Achieved in APS Operation[1]	APS-U Requirements [2]	Allocation for PM IDs[2]	Units
Goals or Performance in rms					
Δx	16	3.5	3	1.0	μm
$\Delta x'$	1.2		0.57	0.17	μrad
Δy	4.4	1.2	0.42	0.1	μm
$\Delta y'$	0.45		0.22	0.055	μrad
Goals in Integrated Power Spectral Density					
Δx			9.0	1.0	μm^2
$\Delta x'$			0.32	0.03	μrad^2
Δy			0.18	0.01	μm^2
$\Delta y'$			0.048	0.003	μrad^2

[1] 0.01 - 100 Hz band.
[2] All permanent magnet IDs, including APPLE, planar and revolver undulators.

various rates. An orbit correction will eventually compensate a step error, but will not be able to correct a perturbation that ramps in time. The resulting error, say, $e(t)$ is equal to the open-loop error orbit rate of change $r(t)$ times the DC correction time constant τ, i.e., $e(t) = r(t)\tau$. The time constant for DC orbit correction at APS is 0.25 seconds. (We might be able to reduce the time constant in the future.) If the ramp doesn't last too long, say, 10 seconds, then the AC-coupled fast orbit feedback (otherwise known as real-time feedback – RTFB) can further reduce the error because of the higher frequency components in the ramp perturbation.

Thus we conclude that the values of the field integrals as a function of gap are not the relevant quantity, rather the derivative is. This can loosen the requirements quite a lot.

The PSD integral from 0.01 to 200 Hz (and other ranges) of the BPM readbacks is continuously calculated by the APS control system with processing that exponentially averages the result with a 1-minute time constant, thus smoothing out spikes. The average over the BPMs at the ID sources will be compared to alarm limits and will be our criterion for stability during operations.

RAMP ERROR WITH FEEDBACK

The orbit perturbation produced by the first- and second-field integral errors of an ID is given by:

$$u(s) = \frac{e}{cp}\frac{\sqrt{\beta_s\beta_o}}{2\sin(\pi\nu)}\sqrt{I_1^2+\frac{I_2^2}{\beta_s^2}} \times \cos\left(|\phi(s)-\phi_s|-\pi\nu\right), \quad (1)$$

$$u_{\max} \approx \frac{e}{cp}\frac{\sqrt{\beta_s\beta_o}}{2\sin(\pi\nu)}\sqrt{I_1^2+\frac{I_2^2}{\beta_s^2}}, \quad (2)$$

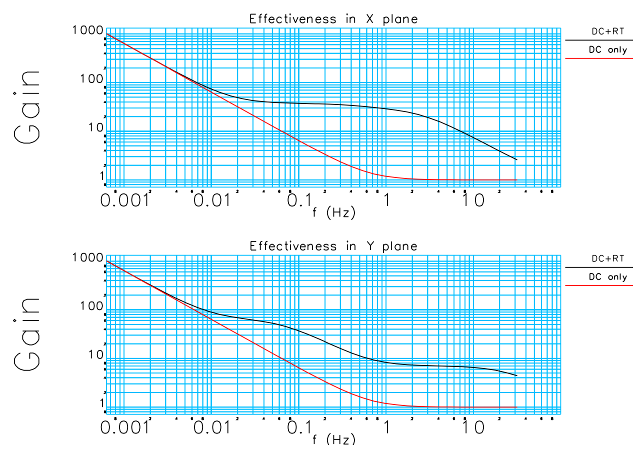

Figure 1: Correction effectiveness with slow correction only ("DC only") and with fast orbit feedback included ("DC+RT")

where u is either x or y; β_s and β_o are the beta functions at the source and the observation location respectively; $I_{1,2}$ are the normalized first- and second-field integrals (i.e., angle and position perturbation, respectively); ν is the betatron tune where we will assume values of $\nu_x = 0.18$ and $\nu_y = 0.22$; and $\phi(s)$ and ϕ_s are the phase advances at longitudinal coordinate s and at the source. The first- and second-field integrals have values roughly independent from each other and different limits will be imposed on each.

Equation (1) obviously indicates that the orbit error induced by a single perturbation is global around the ring, while Equation (2) gives the maximum expected orbit error at some other light source point around the ring. These equations remain valid with integrals and orbit varying slowly with time, of course.

Table 2: Requirements for First- and Second-Field Integral Rate of Change.

Field Integral	**No orbit correction**[1]	**Orbit correction of ramp error, 5-second duration**	**Orbit correction of ramp error, indefinite duration**
Rate of $\int B_y dz$	1.2 G·cm	21 G·cm/s	5.0 G·cm/s
Rate of $\int B_x dz$	1.0 G·cm	16 G·cm/s	4.0 G·cm/s
Rate of $\int dz \int B_y dz'$	2500 G·cm^2	43,000 G·cm^2/s	10,000 G·cm^2/s
Rate of $\int dz \int B_x dz'$	300 G·cm^2	4900 G·cm^2/s	1200 G·cm^2/s

[1] Values in this column are limits on actual field integrals, not their rate.

Most of what follows explains the reduction of the global orbit due to the global orbit correction system. However, even for perfect or infinite time response of orbit correction, there will be remnant local photon beam steering errors because we don't have correcting elements in the straight section. This spatial-domain limitation, though important, will be not be discussed here.

A simple frequency-domain model of the global orbit correction was created using Matlab (building upon scalar-orbit models written by [3, 4]). Since we are interested in the low-frequency part of the response, the effect of time delays and corrector response can be ignored. The results were shown in Figure 1. The gain is found to vary approximately as $1/f$, which is expected for a system under integral control, plus some additional help from the AC-coupled real-time feedback in the important range 0.1 Hz to 1 Hz. Figure 2 shows the time-domain scalar-model orbit response of a unit ramp perturbation (taking orbit and perturbation as unit-less quantities for simplicity). Without correction the orbit error would be equal to the perturbation. With integral correction only (slow orbit feedback),

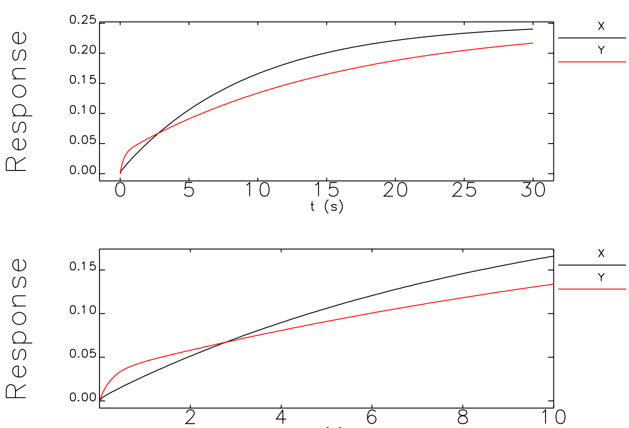

Figure 2: Response to unit-ramp orbit perturbation of our correction system. The average response within the first 5 seconds determines the ID perturbation specification.

the general error would be given by $e(t) = r(t)\tau$, where $r(t)$ = 1 s^{-1} (unit ramp) and τ = 0.25 s in our case. With the additional AC-coupled correction (fast orbit feedback), there is a short-term correction within the first 5 to 20 seconds. Taking the average orbit response over the first 5-second interval, we see that the net orbit response is 0.06 times the ramp rate in both planes. This small factor is reflected in the frequency domain plot of Figure 1, where the average effectiveness in the frequency range 0.1 to 1 Hz is about 20.

Because of the complex frequency dependence of the combined DC-AC system correction effectiveness, the actual orbit "ramp" error from IDs would have to be modeled on a case-by-case basis with orbit correction simulation for acceptance (using the present version of orbit correction).

ID INTEGRAL REQUIREMENTS

Finally we arrive at two sets of ID requirements: one for an arbitrarily long ramp and another (looser) set of stronger allowed perturbations assuming a 5-second ramp. The 5-second ramp-error duration was selected because it matches the worst-case behavior of most planar IDs perturbation.

Table 2 shows the specifications on the first- and second-field integral rates-of-change for these two ramp conditions assuming that each of these integrals will contribute to one half of the ID perturbation allocation of Table 1.

The requirement for the position stability is more severe than that of the angle coordinate, thus only the requirement based on position stability is given in the table.

According to this global orbit error analysis, an ID is allowed to have a somewhat large "peak" in the absolute value of field integrals as long as the peak is not come upon too quickly. One way to make a particularly difficult ID compliant to the rate limit is to make the gap move slowly in the gap-value range where the field integral changes quickly.

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