

Operation of Synchrotron Light Sources with Multiple Insertion Devices*

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Abstract

The stability requirements of the next generation of synchrotron radiation facilities have been achieved on insertion device beamlines of existing rings. However, one insertion device (ID) affects the stored beam and hence the performance of all the other beamlines. Since the effects of the undulators are cumulative, higher levels of performance are required of the accelerator in order to meet and exceed present day standards in rings with many undulators.

This paper will report experience to date in the areas mentioned above at several multi-undulator facilities and efforts to address these problems at facilities in the planning and construction phase. Section II will treat orbit control and feedback. Section III will describe work on linear and nonlinear effects of ideal undulators in accelerators. Section IV will mention undulator imperfections and the demands they make on the accelerator control system.

I. ORBIT CONTROL: FEEDBACK

Orbit stability requirements must be consistent with the emittance of the ring to satisfy all users' needs regardless of differences in beamline designs. For this reason, the motions of the stored beam must be limited to 10% of the rms beamsize and 10% of the rms opening angle at the source point. This corresponds to a 0.5% change in the X-Ray flux through an entrance slit of width equal to twice the rms beam size. Table 1 shows the beam stability requirements at APS and the NSLS X-Ray Ring. The vertical emittances are based on 10% coupling. At APS, the listed vertical motions could be induced by a 1-2 micron displacement of a single quadrupole in the ring or by a changing magnetic field with integrated strength 0.2 gauss · meter. Despite the larger emittance of the NSLS X-Ray Ring, the beam position requirements and the tolerance on quadrupole motions and stray fields are comparable to APS. This is because the beta functions in the ID straight section are much smaller than at APS and the 2.5 GeV NSLS electron beam is less rigid. Feedback orbit control will be essential to achieving the necessary stability.

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Table 1

Orbit Control Requirements at APS and NSLS X-Ray Ring

	ϵ_x	δX	$\delta X'$	ϵ_y	δY	$\delta Y'$
APS	8 nm	30 μm	2 μrad	0.8 nm	9 μm	0.9 μrad
X-Ray Ring	100 nm	37 μm	27 μrad	10 nm	6 μm	17 μrad

Local feedback orbit control systems are in widespread use at synchrotron radiation facilities. The SPEAR ring has 9 local feedback loops installed, servicing 4 ID beamlines. The NSLS X-Ray ring has 10 local loops in use during normal operations.

The performance of a single feedback loop is limited by the sensitivity of the detector, the gain (determined by the loop stability), and the voltage and current available to the steering magnets. When more "local" loops are implemented on a storage ring, deviations from locality of the bumps in one loop result in an interaction with all the other loops in the ring. The interaction can reduce the efficacy of the loops. If the coupling between loops is strong enough, the system of loops could become unstable.

Figure 1 shows a diagram of a feedback loop that controls the amplitude of a local orbit bump so as to null the output of a single beam position monitor. It is configured to reduce the beam motion X observed on the detector by powering a bump that subtracts a quantity x from X. The beam position monitor has an output V proportional to x+X :

$$\text{BPM output } V = X+x$$

but x is produced by a "local" bump whose amplitude is proportional to V:

$$\text{Feedback bump } x = -G * V$$

so that

$$(X+x) = X/(G+1)$$

The ambient beam noise X is reduced by a factor (G+1).

We can generalize this treatment to an array of N "almost independent" feedback loops. The i'th loop has a single beam position monitor. Its output voltage V_i is

intended to create a beam motion x_i that is detected only by the very same (i 'th) monitor. There is a practical limit to how local a bump can be, however. The i 'th BPM still sees only the motion at its own observation point:

$$V_i = X_i + x_i$$

But now the applied correction x_i gets contributions from all the other feedback loops:

$$x_i = - \sum_{j=1}^N G_{ij} V_j$$

Closing the loops results in an orbit correction described by the matrix equation:

$$X + x = (G + 1)^{-1} * X$$

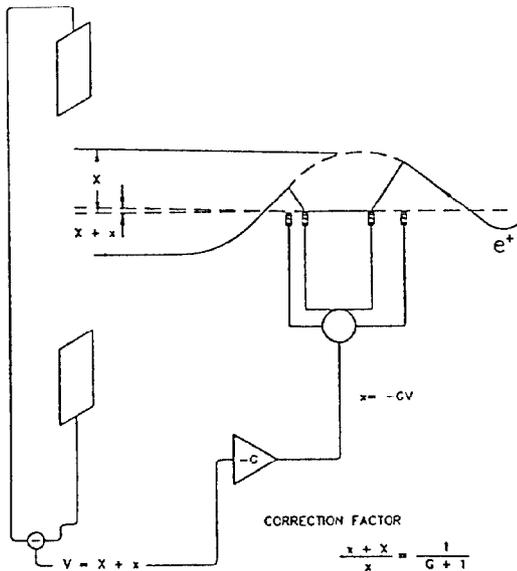


Figure 1. Schematic of local feedback loop - V is the detector output.

In order to have a stable system of N feedback loops, the matrix $(G+1)$ must have a nonzero determinant. We can establish a somewhat stringent condition sufficient for stability by writing

$$(G+1) = g \begin{bmatrix} A_{11} & b_{12} & b_{13} & \dots & b_{1N} \\ b_{21} & A_{22} & b_{23} & \dots & b_{2N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ b_{N1} & b_{N2} & b_{N3} & \dots & b_{N N-1} & A_{NN} \end{bmatrix}$$

where the A 's are all of order one and the b 's are all smaller because they represent the deviations from perfect locality of the feedback correction bumps. The determinant of a matrix M may be written as the sum

$$|M| = \sum_{\text{permutations}} (-1)^P M_{1j_1} M_{2j_2} \dots M_{Nj_N}$$

where p is even if the sequence $j_1, j_2, j_3, \dots, j_N$ is formed from $1, 2, 3, \dots, N$ by an even number of permutations and odd if an odd number of permutations is required. The determinant has one term equal to

$$A_{11} \cdot A_{22} \cdot A_{33} \cdot \dots \cdot A_{NN}$$

and many of terms proportional to products of the A 's and b 's. If we say that all the A_{jj} 's are proportional to a scaling parameter A and all the b_{ij} 's are proportional to another scaling parameter b , we can show that the terms of the sum can be grouped by powers of A and b and we can place an upper limit on how many terms of a given order appear in the sum. We may choose the smallest of the A_{jj} 's to be A and the largest of the b_{ij} 's to be b and we can make the worst-case assumption that all the terms of order $A^{(N-m)}$ have sign opposite to the A^N term.

How many terms in the sum are proportional to $A^{(N-m)} \cdot b^m$? There are $[N!/((N-m)!m!)]$ ways to choose the $(N-m)$ A 's from the set of N A 's available to us. Then we must choose m b 's so that they share no row or column with either the A 's or the b 's we have already chosen. We can overestimate the number of ways to choose the b 's. Once we have selected the $N-m$ rows that will donate their A 's to a given term in the sum, we must choose m off-diagonal matrix elements from the $m \cdot m$ submatrix constructed by eliminating all rows and columns which have donated their A 's. This $m \cdot m$ matrix still contains one A -term and $(m-1)$ b -terms in each row. We overestimate the number of ways we can choose the remaining b 's as $(m-1)!$ since we must choose the b 's so that none share the same row or column in the $m \cdot m$ submatrix. The result is that the sum of all terms of order less than A^N in the determinant is less than

$$\det |G+1| \geq \prod_{j=1}^N A_{jj} - A^N \sum_{m=2}^N \left(\frac{b}{A}\right)^m \frac{N! (m-1)!}{(N-m)! m!}$$

Again we make an overestimate:

$$\frac{N!}{(N-m)!} \leq N^m$$

The determinant is bounded by

$$\det |G+1| \geq \prod_{j=1}^N A_{jj} - A^N \sum_{m=2}^N \left(\frac{Nb}{A}\right)^m \frac{1}{m}$$

If the sum is less than 1, the determinant cannot be zero. Since b measures the deviation of the bump from perfect locality, we conclude that a ring like APS with up to 78 local feedback loops in each plane must have bumps local to about 1% precision just to guarantee stability of the system. The locality condition must be maintained over the working frequency range of the feedback systems, demanding great precision in the matching of frequency response of different steering magnets.

Even if the system of loops is stable, the correction factor may be larger than intended and even greater than one. C. J. Bocchetta and A. Wrulich [1] have studied the

correction factor of stable systems of coupled loops by estimating the worst-case correction factor. They do this by finding the largest eigenvalue for the correction matrix $(1+G)^{-1}$. They investigate some specific error arrangements and prove that, in the case that all the error terms b_{ij} are equal, the stability of the correction requires $b < 1/N$. They go on to investigate transient responses of the system of loops. Their model assumes an iterative correction scheme that samples the beam position. In the worst case, stability required a sampling rate at least twelve times the highest frequency noise to be corrected.

Since the stability margin of a multiloop system is increased as the the number of loops is reduced, global harmonic systems are attractive alternates or supplements to a large number of local feedback loops [2]. Superposition of global and local feedback loops at the NSLS X-Ray Ring showed that global loops and enhance the performance of local loops.

NSLS global feedback systems use analog electronics to process and filter the orbit error signals into analog command voltages to the steering magnets. APS and other machines under construction will utilize digital signal processing and transmission to implement global and local feedback loops. In this case the orbit correction algorithm can emulate local feedback loops, global harmonic feedback, or any other algorithm that proves successful as an orbit correction applications program. This approach requires, however, that the minimum increment in steering magnet current must steer the beam through an angle that is small compared to the stability criterion, i.e., less than one microradian. Furthermore, the correction commands must be obeyed in a time that is short compared to the required response time of the feedback loops, otherwise the digital feedback system will cause transients in orbit motion that exceed the error to be corrected. Fortunately the necessary digital signal processing hardware and high speed communication links are already commercially available. Indeed, the KEK Photon Factory [3] already has a digital global feedback system that consists of an orbit correction application program running continuously in its control computer. The effective bandwidth is a small fraction of a Hertz, but the system is nonetheless a valuable part of PF operations.

II. LINEAR AND NONLINEAR BEAM OPTICAL EFFECTS IN UNDULATORS

The field of an ideal planar undulator has the form

$$B_y = B_0 \cos(k z) \cosh(k y)$$

$$B_z = -B_0 \sin(k z) \sinh(k y)$$

where z is the nominal direction along the beam path and y is vertical. The period of the undulator λ determines k

$$k = 2\pi/\lambda$$

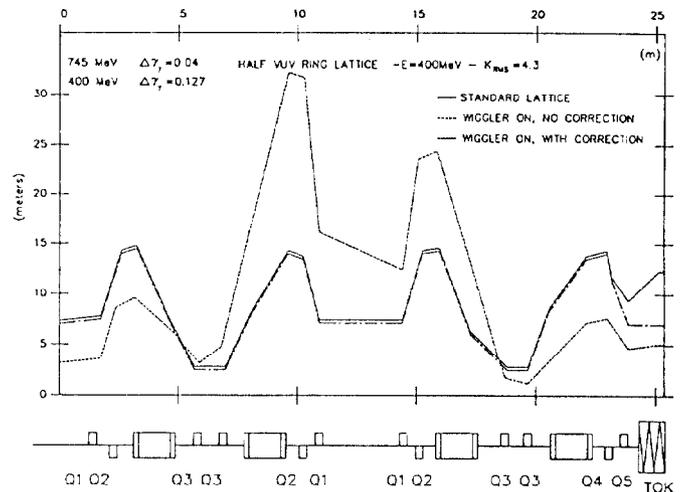


Figure 2. Effect of U13 TOK on vertical betatron functions of the NSLS VUV ring, before and after local correction.

An ideal planar ID would cause absolutely no deflection of the particle beam in the vertical or horizontal direction, and this would be true no matter what the horizontal position or angle of the beam as it enters the device. Even in an ideal ID, however, there is a vertical focussing term. Each pole of the ID causes fringe field focussing, as does any bending magnet.

The vertical focussing of the beam, when averaged over a period of the undulator, is given by [4]

$$y'' + \sinh(2ky)/(4k\rho^2) = 0$$

expanding the hyperbolic sine gives

$$y'' + y/(2\rho^2) + k^2 y^3/(3\rho^2) = 0$$

The linear focussing term has no dependence on the undulator period while the cubic force term increases with the inverse square of the period, for a fixed field. Table 2 lists some insertion devices installed in the NSLS facility as well as devices planned for ALS, APS and ESRF. The table includes computed values for the vertical linear and nonlinear focussing terms $1/(2\rho^2)$ and $(k^2)/(3\rho^2)$, weighted by the average values of the vertical beta functions; $\langle\beta_y\rangle$ for the linear focussing and $\langle\beta_y^2\rangle$ for the cubic force.

The detrimental effects of the ID on the particle optics may be resolved into two mechanisms. First, the linear focussing breaks the symmetry of the lattice and consequently the symmetry of the beta functions and phase advances. This effect may be compensated to various levels of precision by adjusting the quadrupoles in the ring. The simplest correction is to scale all the quadrupole currents to restore the betatron tunes. By using only the quadrupoles nearest the ID, the distortion of the betatron functions can be localized within the superperiod that contains the ID. This action will generally cause an error in betatron tune which can be corrected with a global adjustment involving almost all the quadrupoles. This "alpha-matching" technique is

Table 2

	ESRF	ALS		NSLS X-Ray Ring			NSLS VUV RING		APS	
	Undulator	U3.65	U20.0	X1	X17	X25	U5 APS	U13 TOK	Undulator A	Wiggler A
Bo (Tesla)	0.45	0.61	1.1	0.35	5.0	1.1	.46	.65	0.86	1.0
λ (cm)	4.4	3.65	20.0	8	17.4	12	7.5	10.	3.1	15
L (m)	1.6	4.9	4.6	3	0.6	1.7	2.1	2.2	2.5	1.5
Δv_y	.0005	.007	.02	.0005	.004	.001	.016	.034	.0113	.0011
A*	675	8484	820	154	18	35	5163	6065	4650	160
*A = $4\pi^2 \langle B^2 \rangle L / (3\rho^2 \lambda^2)$ (m ⁻¹)										

exemplified in Figure 2, which shows the uncorrected and corrected betatron functions of the NSLS VUV ring with the U13 TOK undulator installed.

Third-generation synchrotron radiation facilities are much less tolerant of asymmetries in phase advance than are other rings. This is true whether the asymmetry is caused by the vertical focussing of undulators or closed orbit errors in the sextupoles. A reasonable dynamic aperture can be achieved in such rings only by careful placement of the very strong chromaticity-correction sextupoles, or else by partially cancelling the effect of the chromaticity-correction sextupoles with additional families of harmonic-correction sextupoles. In principle, the linear focussing effects of the ID could be compensated perfectly. One simply needs enough flexibility in adjusting the neighboring quadrupoles to keep the transfer matrices between sextupoles independent of the ID strength. In practice, other lattice imperfections may mask the potential improvement of a "perfect" linear compensation.

The lowest-order nonlinear focussing force of an undulator has a cubic dependence on y so one can expect stopbands around $4v_y = \text{integer}$.

The effects of undulators on ALS has been studied by Jackson, et al. [5]. They compared schemes for correcting the linear focussing and concluded that one may use the defocussing quads nearest the ID to correct the vertical tunes. The horizontal tune correction may then be distributed globally over almost all the horizontal focussing quads. They find that the linear and nonlinear focussing properties of the IDs reduce the dynamic aperture by similar amounts, and that the effect of the IDs is also comparable to the effect of magnet imperfections. Although the undulators reduce the vertical dynamic aperture significantly, it remains larger than the physical aperture.

Tosi and Nagaoka have investigated the effect of helical undulators and variable-polarization IDs in Elettra [6]. IDs that produce circularly polarized radiation generally act like optical elements with both vertical and horizontal focussing.

Undulators planned for ESRF [7] have fields and periods consistent with the 20 mm vertical aperture of the ID straight section. The ESRF ring energy is threefold that of ALS and

its undulators have longer period lengths. Hence one expects and finds smaller changes in dynamic aperture than those seen in ALS and Elettra. Like ESRF, linear focussing effects of undulators are very small in APS. Studies of nonlinear effects of undulators are not yet complete.

Evidence of the effect of IDs on particle optics and dynamic aperture have been measured and reported by Brunelle for Super ACO [8] and by Kuske and Bahrdrdt at BESSY [4]. In both rings, the effect of the cubic force on dynamic aperture was investigated by measuring the beam lifetime as a function of tune with the sextupole magnets turned off. Lifetime reductions in reasonable agreement with results of computer simulations of the dynamic aperture were obtained in both cases.

Detailed studies of the effects of the Phase II insertion devices of the NSLS X-Ray ring at 2.5 GeV are yet to be completed. However, their linear and cubic force terms are expected to have little effect because the vertical β function is only 0.35 meters in the ID straight section. Studies involving beam optical effects of the IDs will be done at 0.75 GeV, the injection energy of the X-Ray ring.

III. UNDULATOR IMPERFECTIONS

The imperfections of a state-of-the art ID should be too small to significantly affect dynamic aperture of a typical synchrotron radiation ring. However even minor field errors can disturb the orbit and linear coupling if the strengths of the undulators are changed during operations. Steering errors caused by gap changes in IDs must be compensated by feedback and by steering magnets that are programmed to change as a function of ID strength.

If the need for orbit stability is driven by the need for highly stable flux into the acceptance of the photon beamlines, then it must also be necessary to have a high level of stability in the skew quadrupole fields as the IDs change gap. If we demand 0.5% stability in photon flux through a 2σ slit that limits the beam vertically, this implies that the vertical emittance must be stable to 2%. The linear coupling must therefore be held constant to 2% of its value; for APS the nominal 10% coupling must remain in the range 9.8%-

10.2% to fulfill this criterion. The undesirable consequences of a beam size change caused by magnetic imperfections in an ID, at SRC in Stoughton, Wisconsin, were reported by Trzeciak, et al. [9]. Ironically the increased coupling caused by changing the gap of the ID improved the beam lifetime by increasing the volume of the bunch and thereby reducing the Touschek loss rate.

The tolerance on the change in linear coupling can be converted to a magnetic field tolerance for APS; the skew quadrupole of an undulator must change less than 65 gauss as the gap changes. Measurement techniques with the necessary sensitivity have been developed and applied, for example, to the NSLS Phase II IDs [10]. Such magnet measurements demonstrate that this specification has been exceeded by the APS undulator in the U5 beamline at NSLS, which has a total (normal + skew) quadrupole integral of 10 gauss [11].

Conceptually simple ingredients are necessary if synchrotron radiation users are to be permitted to change ID strength at will. The problem is not trivial as evidenced by the fact that, at NSLS, SPEAR, SRC, Super ACO and Daresbury SRS, ID strengths are not changed routinely during operations for many users, although gap changes are permitted at SRS. SPEAR and SRC intend to implement independent gap changes on certain devices in these rings in the near future.

While the beam stability can be affected by quite small imperfections in IDs, the most important effects are fortunately linear so that the effects of individual IDs and their corrections should satisfy superposition. This means that, if the accelerator controls system is configured to accommodate it, a matrix can be defined that specifies the vector of necessary changes in all accelerator parameters in terms of the vector of all ID strengths. The necessary changes can then be implemented automatically by the controls system as the users change gaps of the IDs.

SSRL beamlines 5,6 and 10 are configured so that steering corrections are automatically updated to track changes in magnet strength. After further studies, users will be allowed to change strength of the undulator at beamline 5. For the present, undulator strengths at SSRL are changed during operations only after all users have been notified.

Alladin has implemented automatic gap-dependent compensation of orbit errors so that no motions larger than 20 microns (vertical) or 50 microns (horizontal) are caused by changing the undulator gap. The change in vertical beam size that is coupled to gap changes must be corrected automatically before unannounced gap changes will be allowed.

NSLS allows changes of the X1 soft X-Ray undulator strength during operations. The X1 users call the control room to request a change and the ring operators make the change after notifying all users.

Only at the KEK Photon Factory are unannounced gap changes routinely performed in operations. Each of five IDs has a prescribed range over which it may be changed without disturbing orbit stability.

The problems to be solved in operating synchrotron radiation rings with many IDs have been and continue to be studied at facilities presently in operation. With sufficient care and attention to detail, any problems caused by steering errors and linear focussing properties in the undulators can be corrected by feedback or by commanding the necessary steering and quadrupole adjustments in coordination with ID strength changes. Nonlinear focussing effects may reduce the beam lifetime, but this can be an acceptable price to pay for the use of short-period undulators.

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