CONF-960848--44

Performance optimization of synchrotron light sources *

J. Safranek for the NSLS Staff

National Synchrotron Light Source
Brookhaven National Laboratory

Upton, NY 11973

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ABSTRACT

This paper will present work done at the NSLS to tailor the electron beam properties so as to maximize the performance of the photon beamlines. The electron beam properties of most importance to photon users are the total stored current, emittance, lifetime, and transverse stability. Recent and planned improvements in each of these properties will be discussed as well as the ultimate limits for each. The discussion of transverse stability will include high frequency motion, which can reduce the effective brightness, as well as slow drift during a fill and fill-to-fill reproducibility.

1 ORBIT STABILITY

The stability requirements on the orbit of the stored electrons in synchrotron radiation sources have increased as the brightness of the storage rings has increased. Ideally, one would like the the orbit motion to be a small fraction of the electron beam size, so the high brightness is not compromised. Fill-to-fill reproducibility, small orbit drift over the course of each fill, and small orbit jitter all are important for maximizing the utility of the synchrotron light.

1.1 Orbit correction

MASTER

Just after each new fill, the orbit is corrected in order to maximize fill-to-fill reproducibility. The orbit is corrected using steering magnets to adjust the measured orbit at the electron beam position monitors (BPMs). The change of the orbit at the BPMs ($\Delta\vec{x}$) from a change in steering magnet strengths ($\Delta\vec{\theta}$) is linear to a good approximation, so it can be described with a matrix, M , called the orbit response matrix.

$$\Delta\vec{x} = M\Delta\vec{\theta} \quad (1)$$

Orbit correction simply consists of inverting this matrix to find those steering magnet strengths that give the desired change in orbit. The difficulty is that the matrix M is ill-conditioned, so it does not have a well-defined

*Work performed under the auspices of the U.S. Department of Energy

inverse. Two algorithms for inverting ill-conditioned matrices are used with good results for orbit correction at the NSLS: singular value decomposition (SVD)¹ and regularization.² According to the electron BPMs the typical shift of the orbit in the X-Ray Ring from fill to fill is 50 μm rms horizontal and 9 μm rms vertical, (where the rms is a spatial rms over the 48 BPMs). These shifts are only about 5 % and 28 % of the horizontal and vertical rms electron beam sizes. For those BPMs just upstream and downstream of insertion devices, the orbit according to the BPMs is reproduced to a few microns both horizontally and vertically. An explanation of why the modifier 'according to the BPMs' is included will come in section 1.3.

1.2 Orbit feedback

Once the orbit has been corrected at the top of each fill, orbit feedback systems are turned on to keep the orbit from drifting over the course of the fill and to remove higher frequency orbit jitter from sources such as ground motion and power supply ripple. The first orbit feedback systems were local feedback systems developed at the Stanford Synchrotron Radiation Laboratory in the early 1980's.³ The NSLS X-Ray Ring now has six local feedback systems. These local feedback systems use four orbit steering magnets, two upstream and two downstream of each insertion device to make local orbit bumps that keep the orbit fixed on two BPMs, one upstream and one downstream of the insertion device. The local feedbacks are analogue systems with gain curves that cross 0 dB at 50 Hz. The local feedbacks keep the orbit drift as measured by the BPMs in the feedback loops to less than 1 μm vertical and less than 2 μm horizontal.

In addition to the local feedbacks that stabilize the orbit at the insertion devices, the X-Ray Ring has analogue and digital global orbit feedback systems designed to minimize orbit variations throughout the ring. The global systems stabilize the orbit at the dipole beamline source points and increase the orbit stability at the insertion devices. The analogue system^{4,5} was commissioned in 1989 and was the winner of an R&D 100 award. It uses one third of the available BPMs and steering magnets in the X-Ray Ring. Just as with orbit correction, the response matrix between the BPMs and steering magnets is ill-conditioned, so it does not have a well defined inverse. The trick used in the analogue global feedback to avoid this problem is to correct spatial harmonics of the orbit shifts rather than the individual orbit shifts themselves. An electron beam in a storage ring has natural transverse oscillation frequencies horizontally and vertically which are called the tunes of the storage ring. For example, in the X-Ray Ring if the beam is kicked horizontally it oscillates about the closed orbit 9.14 times each revolution around the ring, so the horizontal tune is 9.14. When a steering magnet strength is changed, the Fourier series of the resulting closed orbit shift is largest for spatial frequencies near the tune. Correcting just a few spatial frequencies around the tune removes most of the orbit shift. In the X-Ray Ring the global analogue feedback corrects the two phases for each of the four spatial harmonics closest to the tune in both the vertical and horizontal planes. The feedback gain curves cross 0 dB at 150 Hz.

The global analogue feedback has provided excellent orbit stability. For most users, the level of this beam stability (short and long-term) has been satisfactory, however, further stabilization is desirable. For this reason a global digital feedback has recently been developed.⁶ The digital feedback uses all the available BPMs and steering magnets. Just as with orbit correction, the digital feedback uses singular value decomposition to invert the orbit response matrix. It has a 10 Hz bandwidth and has high gain (36 dB) at DC, so it is very effective at reducing orbit drift during a fill.

Figure 1 shows the orbit drift at representative BPMs during a 9 hour fill with the local, analogue global and digital global feedbacks all running together. The orbit drift at the insertion device BPMs is 2 μm or less both horizontally and vertically. The orbit drift around the ring is about 22 μm rms horizontal and 7 μm rms vertical according to the BPMs, which corresponds to about 2.3% horizontal and 22% vertical of the rms transverse electron beam dimensions. Without the feedback systems the orbit drifts would be on the order of hundreds of microns.

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Figure 1: This shows the typical measured motion on electron BPMs over the course of a nine hour fill with both analogue and digital orbit feedbacks running. The stored current decayed from 300 to 170 mA over the nine hours. Arbitrary offsets have been added for plotting clarity. The digital resolution is about $2.4 \mu\text{m}$ per bit for the above measurements. (Recently the digital resolution has been increased to $0.6 \mu\text{m}$ per bit.)

Figures 2 and 3 show spectral analyses of orbit jitter without and with the orbit feedback systems. The orbit feedbacks reduce rms orbit motions for frequencies above 1 Hz from about $11 \mu\text{m}$ horizontal and $3 \mu\text{m}$ vertical to $1.5 \mu\text{m}$ and $1 \mu\text{m}$. This corresponds to about 0.1% and 2% of the rms horizontal and vertical beam sizes.

Figure 2: Spectral analysis of vertical and horizontal orbit motion without orbit feedback.

Figure 3: Spectral analysis of vertical and horizontal orbit motion with orbit feedback.

Table 1 gives a summary of the orbit stability achieved in the X-Ray Ring according to the BPMs with all orbit feedbacks running.

Table 1. Orbit stability according to the electron BPMs with all orbit feedbacks. The rms figures are rms over all 48 BPMs in the X-Ray Ring. The stability at the insertion device BPMs is significantly better. The percentages given in parenthesis are fractions of the rms electron beam size.

	horizontal rms	vertical rms
fill-to-fill	50 μm (5%)	9 μm (28%)
orbit drift	22 μm (2.3%)	7 μm (22%)
orbit jitter	1.5 μm (0.1%)	1 μm (2%)

The X-Ray Ring digital feedback will be upgraded in the future to increase the bandwidth from 10 Hz to 200 Hz, which will possibly eliminate the need for the analogue feedbacks. This is the direction that the third generation light sources are taking.

Another type of orbit feedback worth mentioning is done by varying the frequency of the rf cavities in order to take out orbit drifts that are not removed with the steering magnet feedbacks. Such an algorithm is used at the NSLS VUV Ring, where the orbit drift over several hours of a typical fill with only the steering magnet orbit feedbacks shows a strong component with the characteristic of the orbit shift induced by changing the rf frequency. Varying the rf frequency during the fill takes out this component and reduces the rms horizontal orbit drift by a factor of six.

1.3 Orbit stability limitations

The orbit stability figures presented in table 1 were stated as measured by the BPMs, so they would give the correct measure of orbit stability if the BPMs were perfectly stable mechanically and electrically. Such is not the case. The BPM electronics are remarkably stable^{7,8} with a dynamic stability better than a few μm over the range of stored electron current in a typical fill (150 to 300 mA). The mechanical stability is not as good and presently

limits the achievable fill-to-fill orbit reproducibility and long-term stability during each fill.

As the vacuum chamber heats and expands from synchrotron radiation, the beam position monitors (BPMs) also move.⁹ In each superperiod of the X-Ray Ring, a rigid vacuum chamber support near Q4 (see figure 4) fixes the chamber position in all three dimensions. The chamber is free to expand longitudinally between Q4 and the bellows, which are located at the end of the insertion straight section. Several supports between the three-dimensional fixed point and the bellows minimize transverse horizontal and vertical motion while permitting the longitudinal expansion. Despite these supports, the large forces associated with the vacuum chamber expansion lead to significant motion of the vacuum chamber in the transverse horizontal direction in certain locations as well as small vertical motions.

Figure 4: This is a schematic of the layout of one of the 8 superperiods in the X-Ray Ring. The quadrupole, dipole, and BPM locations are shown.

Gauges installed at several BPMs have measured the transverse movement of the vacuum chamber. Figure 5 shows the largest measured motion, which was transverse horizontal motion at BPM 5 in the sixth superperiod. The largest chamber movements are at the fifth BPM in each superperiod, because it is just downstream of the dipole magnet (figure 4) where synchrotron radiation heating is largest. A large chamber movement (about 300 μm in figure 5) occurs as the ring energy is ramped to 2.584 GeV, when the synchrotron radiation begins heating the chamber. The vacuum chamber is cooled by temperature regulated water, but even with the inlet water temperature held fixed, the outlet water temperature heats 1.8 degrees C from the synchrotron radiation. After the initial large motion which lasts about 10 minutes, there is a slow drift in the chamber position as the synchrotron radiation load decreases due to stored current decay.

Table 2 shows the size of the initial horizontal motion (the first 5 to 10 minutes of the fill) and the subsequent drift in the vacuum chamber over the succeeding hours of the fill for the BPMs measured so far. The limit on the long-term horizontal orbit stability of the X-Ray Ring is set by the 'subsequent' vacuum chamber motion, since the orbit motions associated with the feedback systems (table 1) are much smaller. The orbit stability is probably somewhat better than the figures given as 'subsequent' motion, because the orbit steering magnets are most effective at removing spatial harmonics associated with real orbit motion, not the spatial harmonics associated with apparent orbit motion due to BPM movement. The orbit correction is usually done 5 to 10 minutes into the fill, so the orbit is corrected to a moving target. Thus the fill-to-fill reproducibility is compromised by the 'initial' motion.

Figure 5: This shows the horizontal motion of the vacuum chamber at BPM 5 in the sixth superperiod as the beam is dumped and refilled. Time zero is the time the ring energy was ramped from injection energy (744 MeV) to operation energy (2.584 GeV).

Table 2. The initial motion is the horizontal movement of the BPM in the first 5 to 10 minutes of the fill. The subsequent motion is the movement in the following several hours of the fill.

BPM	Superperiod	Initial Motion	Subsequent Motion
2	8	20 μm	< 10 μm
3	2	0 μm	0 μm
4	2	60 μm	50 μm
5	1	90 μm	60 μm
5	6	300 μm	70 μm
5	7	240 μm	85 μm
6	7	40 μm	

The vertical motion of the vacuum chamber was measured at the two BPMs with the largest measured horizontal motion. Both had initial measured vertical motions of less than 20 μm . This sets a rough upper bound on the vertical BPM motion. The surface of the vacuum chamber where the motion measurements were made was not a machined reference surface, so some of the measured vertical motion could be a false reading associated with the much larger transverse horizontal and longitudinal motions of the BPMs. Subsequent measured vertical motion over the succeeding hours of the fill was even less, and the motion at BPMs where the vacuum chamber sees less synchrotron radiation is expected to be smaller still.

Studies are in progress to determine how best to compensate for the measured BPM motions. If the motion is determined to be sufficiently reproducible from fill to fill, the feedback systems will be modified with a correction factor that varies with the stored current and the time after the top of the fill. If the BPM motion is not sufficiently reproducible, the vacuum chamber motion will have to be measured real-time and compensated in the feedback.

2 FLUX AND BRIGHTNESS

The flux and brightness are two parameters that give a good description of the performance of a synchrotron light source.¹⁰⁻¹³ The flux is a measure of the total number of photons available to a beamline. The brightness is a measure of the density of those photons in four-dimensional transverse phase space – the flux per unit area per unit solid angle. A brighter photon beam has higher collimation, can be focused to a smaller spot, and has a greater degree of transverse coherence.

Both flux and brightness scale linearly with electron current, so efforts are underway to increase the current in the X-Ray Ring. In December, 1993, the number of rf cavities in the X-Ray Ring was increased from three to four, to provide the additional rf power required for increased stored current.¹⁴ The peak stored current was subsequently increased from 250 to 300 mA, and is limited by thermal loading on the beamline beryllium windows. Beryllium window upgrades are now in progress, and the stored current will be increased to 440 mA in the near future. In order to increase the current beyond 440 mA, the entire vacuum chamber would have to be rebuilt to handle the additional synchrotron radiation power. As is discussed in reference,¹⁵ the technology is available to increase the stored current to 2.4 Amps. With such an upgrade the X-Ray Ring beamlines would have the higher flux over the entire photon spectrum than ALS or APS. The brightness of the X-Ray beamlines would be similar to that for ALS and APS.

The brightness of the synchrotron light can be increased by decreasing the phase space area of the electron beam in order to decrease the phase space area of the photon beam at the beamline source. The horizontal emittance, ϵ_x , gives a measure of the phase space area of the electron beam in (x, x') , and the vertical emittance, ϵ_y , gives the area in (y, y') . (The derivatives are with respect to position along the orbit of the electrons.) The total transverse phase space area of the electron beam is the product of ϵ_x and ϵ_y . Usually the brightness of a dipole or a wiggler synchrotron radiation source scales approximately as the inverse of $\sqrt{\epsilon_x \epsilon_y}$, while the brightness of a undulator scales somewhere between the inverse of $\epsilon_x \epsilon_y$ and the inverse of $\epsilon_x \sqrt{\epsilon_y}$, depending on the details of the undulator and ϵ_y .

The horizontal emittance is determined by the storage ring lattice optics (the placement of dipole and quadrupole magnets and the focusing strengths of the quadrupoles as determined by their magnetic gradients). All electrons in a storage ring oscillate about a closed orbit. These oscillations are called betatron oscillations. Because electrons with higher energies bend less in the dipoles, there is a shift in orbit with energy called the dispersion. The lattice optics determine the dispersion. When an electron emits a photon, the electron energy is reduced. If the photon is emitted at some location with nonzero horizontal dispersion, the electron starts betatron oscillations about a new closed orbit associated with the change in energy and the dispersion function. This is called quantum excitation of betatron oscillations. The horizontal emittance gives a measure of the rms size of the horizontal oscillations excited by the quantum excitation. Synchrotron radiation occurs in dipole magnets, so to achieve small emittance it is important to maintain small dispersion in the dipole magnets. Once a storage ring has been built and the structure is fixed, usually some additional reduction in horizontal emittance can be achieved by adjusting the quadrupole gradients to reduce the dispersion in the dipoles in order to reduce the quantum excitation. For example, this was done at SSRL,¹⁶ and more recently at ESRF. Similar work is underway at the NSLS X-Ray Ring with the goal of reducing the horizontal emittance by a factor of two.

The vertical emittance of a storage ring is determined not so much by the lattice design, but by rotational misalignments of the quadrupoles and vertical misalignment of the electron closed orbit in the sextupoles. Both of these misalignments results in skew magnetic gradients that couple horizontal betatron oscillations into the vertical plane. In order to reduce the coupling and in doing so reduce the vertical emittance, skew quadrupole correction magnets are installed in storage rings and powered to cancel the effect of skew gradients from sextupoles and rotated quadrupoles.

A novel technique for determining the strengths of the skew quadrupole correctors was developed on the X-Ray Ring.¹⁷ The technique is based on closed orbit measurements. In addition to coupling horizontal betatron

oscillations into the vertical plane, skew gradients also couple horizontal closed orbit shifts into the vertical plane. The coupling correction technique is based on powering the skew quadrupole correction magnets to minimize the measured vertical closed orbit shifts associated with the horizontal steering magnets. With this method, the measured vertical emittance has been reduced to 0.1 nm*rad which gives an unusually small vertical to horizontal emittance ratio of 0.1%.¹⁸ This coupling correction algorithm has also recently been used to reduce the vertical emittance at ESRF.¹⁹

3 LIFETIME

In most synchrotron radiation sources the lifetime is determined by the Coulomb scattering lifetime (τ_C), the bremsstrahlung lifetime (τ_b), and the Touschek lifetime (τ_T). The lifetime of the stored beam is given by

$$\frac{1}{\tau} = \frac{1}{\tau_C} + \frac{1}{\tau_b} + \frac{1}{\tau_T} \quad (2)$$

The Coulomb scattering and bremsstrahlung lifetimes are associated with elastic and inelastic scattering of stored electrons off gas and are determined, for the most part, by the quality of the vacuum and the size of the vacuum chamber, though the details of the electron beam optics and rf system do make some difference. The Touschek lifetime is associated with electrons getting lost from the ring when one stored electron collides with another stored electron. The probability of a collision goes up as the bunch density goes up, so the Touschek lifetime is inversely proportional to the volume of the electron bunches. High brightness requires that the electron beam is small in the two transverse dimensions, so as the brightness increases the Touschek lifetime decreases.

Figure 6: A fourth harmonic rf cavity was added to the VUV Ring to reduce the slope of the rf voltage at the synchronous phase. In this way the electron beam lifetime was doubled.

One way to increase the Touschek lifetime without compromising brightness is to lengthen the bunches. This has been done using a fourth harmonic cavity on the NSLS VUV Ring.²⁰ The rf system in a storage ring both replenishes the energy lost to synchrotron radiation and provides longitudinal focusing of the electron bunches. The stored electrons oscillate about the synchronous phase of the rf, which is that phase at which the rf voltage equals the energy lost to synchrotron radiation. To first order, the strength of the longitudinal focusing is

proportional to the slope of the rf voltage at the synchronous phase. Figure 6 shows how an additional rf cavity running at the fourth harmonic of the 53 MHz fundamental has been used to reduce the slope at the synchronous phase to zero. In this manner the length of the bunches was increased, and the lifetime in the VUV Ring was increased by a factor of two (figure 7).

Figure 7: The decay of stored current with time is shown for the VUV Ring with and without the fourth harmonic (211 MHz) cavity. The fourth harmonic rf cavity gave about a factor of two improvement in lifetime.

Even with the fourth harmonic cavity, the VUV Ring is usually not operated with the maximum possible brightness. In order to increase the Touschek lifetime, the VUV Ring is run with a vertical emittance more than a factor of three times larger than the minimum achievable emittance. One could avoid this compromise between lifetime and brightness by using top-off injection.²¹ With top-off injection, additional beam is injected regularly (say every 10 minutes or so), so that the total stored current stays relatively constant with time regardless of the lifetime. This method has the additional benefit of reducing problems due to varying heat loads in the storage ring (see section 1.3), and on the beamline optics.

4 ACHIEVING DESIGN PERFORMANCE

The measured optics of a storage ring never completely agree with the predictions from computer models of the storage ring design. Errors in the magnetic gradients in the quadrupole magnets as well as gradients in insertion devices and sextupole magnets lead to distortions of the β -functions and dispersion as well as coupling between the horizontal and vertical planes. (The horizontal and vertical β -functions give measures of the horizontal and vertical size of the electron beam as a function of position around a storage ring. The size varies as $\sqrt{\beta}$.) Such distortions usually degrade the performance of the ring in terms of brightness, lifetime and injection efficiency. Figures 8, 10 and 12 show examples of optics distortions in synchrotron radiation storage rings.

Recently, a method has been developed for determining the gradient errors in storage rings and for finding the best correction to restore the design optics.^{22,23} The data used in this analysis is the measured orbit response matrix, defined in equation 1. The orbit response matrix contains a large number of data points (for example 8640 in the X-Ray Ring) that reflect the magnetic gradient distribution in the storage ring. The method for determining

the gradients is to modify the parameters of a computer model of the storage ring in order to minimize the chi-square difference between the orbit response matrix predicted by the computer and the measured orbit response matrix. The parameters varied include the calibrations and rotational alignment of each of the quadrupole magnets, the BPMs, and the orbit steering magnets. In all 626 parameters were varied to fit the 8640 data points for the X-Ray Ring. The 626 parameters could be determined to a surprising accuracy. For example, the gradients in each of the quadrupole magnets was determined to within nearly .04%.

Figure 8: Due to magnetic gradient errors in the X-Ray Ring, the measured horizontal dispersion (η_x) does not have the design eight-fold periodicity.

Figure 9: Using the measured orbit response matrix, the gradient errors in the X-Ray Ring were determined, so the storage ring model accurately predicts the measured horizontal dispersion.

The computer models fit with the response matrix give much better predictions of other measurements of the storage ring optics, as is shown for the X-Ray Ring dispersion in figure 9. Controlling the horizontal dispersion in the dipole magnets is critical for minimizing the horizontal emittance and maximizing the brightness of the synchrotron light. With the improved understanding of the X-Ray Ring optics, work is now underway to correct the horizontal dispersion distortions and reduce the horizontal emittance by as much as a factor of two.²⁴

As was stated in section 2, the vertical emittance of a storage ring is determined predominantly by skew gradient errors in quadrupoles and sextupoles. From the orbit response matrix analysis, the skew gradient in each magnet of the X-Ray Ring is known. This improved knowledge of the ring optics will be used in future work to further reduce the vertical emittance and thereby increase the brightness of the beamlines.

Figure 10: The β -functions in the NSLS VUV Ring did not have the design four-fold periodicity.

Figure 11: With the orbit response matrix analysis, the design periodicity of the VUV Ring was very nearly restored, despite the focusing in the insertion devices, quadrupole gradient errors, and focusing in sextupoles.

The orbit response matrix analysis can also be used to find what changes should be made to the quadrupole strengths in order to best compensate for gradient errors in sextupoles, insertion devices, and the quadrupoles themselves. In this way the periodicity of the design optics can be restored. Figure 11 shows the optics that were achieved in this manner with the NSLS VUV Ring. Restoring the design periodicity in the VUV Ring increased the lifetime by about 20 % without reducing the brightness. Figure 13 shows the optics that were obtained in the ALS Ring. When the design periodicity was restored in the ALS Ring, the injection rate increased by about a factor of two.

Figure 12: The vertical β -function in the ALS Ring did not have the design twelve-fold periodicity.

Figure 13: With the orbit response matrix analysis, the design periodicity of the ALS Ring was very nearly restored, despite the focusing in the insertion devices, quadrupole gradient errors, and focusing in sextupoles.

5 ACKNOWLEDGEMENTS

The work described in this paper is the work of many people at the National Synchrotron Light Source and elsewhere. I particularly want to express my appreciation for help with this manuscript to Rich Biscardi, Wayne Broome, Steve Hulbert, Steve Kramer, Gloria Ramirez and Om Singh.

6 REFERENCES

- [1] E. Bozoki and A. Friedman, Optimization Method for Orbit Correction in Accelerators, *Proceedings of the 1993 IEEE Particle Accelerator Conference*, 105-107.
- [2] Y.N. Tang, Use of Regularization Method in the Determination of Ring Parameters and Orbit Correction, *Proceedings of Orbit Correction and Analysis in Circular Accelerators Workshop*, AIP Conf. Proc. No. 315, (AIP, New York, 1994), 87-94.
- [3] R.O. Hettel, *IEEE Trans. Nucl. Sci.* NS-30 (1983), 2228.
- [4] L.H. Yu et al., Real Time Global Orbit Feedback System for NSLS X-Ray Ring, *Proceedings of the 1991 IEEE Particle Accelerator Conference*, 2542-2544.
- [5] O. Singh Electron Beam Stability and Beam Peak to Peak Motion Data for NSLS X-Ray Storage Ring, *Proceedings of the 1993 IEEE Particle Accelerator Conference*, 2254-2256.
- [6] A. Friedman, E. Bozoki, A Digital Feedback System for Transverse Orbit Stabilization, *Proceedings of the 1994 European Particle Accelerator Conference* 1586-1588.
- [7] R. Biscardi and J.W. Bittner, Switched Detector for Beam Position Monitor, *Proceedings of the 1989 IEEE Particle Accelerator Conference*, 1516-1518.
- [8] R. Nawrocky et al., manuscript in preparation.
- [9] E. Johnson, A.M. Fauchet, X. Zhang, Correlation of Photon Beam Motion with Vacuum Chamber Cooling on the NSLS X-Ray Ring, *Rev. Sci. Instrum.* 63 (1), January, 1992.
- [10] G.K. Green, Spectra and Optics of Synchrotron Radiation, Brookhaven National Laboratory Report 50522, 1976.
- [11] S. Krinsky, M.L. Perlman and R.E. Watson, Characteristics of Synchrotron Radiation and of its Sources, *Handbook on Synchrotron Radiation, Vol 1., Chapter 2*, North-Holland, 1983.
- [12] K.J. Kim, Characteristics of Synchrotron Radiation, *U.S. Particle Accelerator School 1987 and 1988*, AIP Conf. Proc. No. 184, (AIP, New York, 1989), 565-632.
- [13] S.L. Hulbert and J.M. Weber, Flux and Brightness Calculations for Various Synchrotron Radiation Sources, *Nucl. Instr. and Meth.* A319 (1992), 25-31.
- [14] M.G. Thomas et al., NSLS X-Ray RF System Upgrade, *Proceedings of the 1993 IEEE Particle Accelerator Conference*, 1419-1420.
- [15] E.B. Blum, X-324: An Upgrade to the NSLS X-Ray Ring Using B Factory Technology, Brookhaven National Laboratory Report 49795, 1993.
- [16] J. Safranek and H. Wiedemann, A Low-Emittance Lattice for SPEAR, *Nucl. Instr. and Meth.* A319 (1992), 18-24.

- [17] J. Safranek and S. Krinsky, Coupling Correction Using Closed Orbit Measurements, *Proceedings of Orbit Correction and Analysis in Circular Accelerators Workshop*, AIP Conf. Proc. No. 315, (AIP, New York, 1994), 163-169.
- [18] J. Safranek and P.M. Stefan, Manuscript in preparation.
- [19] A. Ropert, Private communication.
- [20] R. Biscardi, S.L. Kramer and G. Ramirez Bunch Length Control in the NSLS VUV Ring, *Nucl. Instr. and Meth. A366* (1995), 26-30.
- [21] S. Kramer, Private communication.
- [22] J. Safranek and M.J. Lee, Calibration of the X-Ray Ring Quadrupoles, BPMs, and Orbit Correctors Using the Measured Orbit Response Matrix, *Proceedings of Orbit Correction and Analysis in Circular Accelerators Workshop*, AIP Conf. Proc. No. 315, (AIP, New York, 1994), 128-136.
- [23] D. Robin, J. Safranek, G. Portmann and H. Nishimura, Model Calibration and Symmetry Restoration of the Advanced Light Source, *Proceedings of the 1996 European Particle Accelerator Conference*.
- [24] J. Safranek, A Low Emittance Lattice for the X-Ray Ring, *Proceedings of the 1995 IEEE Particle Accelerator Conference*, 266-268.