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Conf-8908288--1

BNL - 46615

**STORAGE RING DEVELOPMENT AT THE
NATIONAL SYNCHROTRON LIGHT SOURCE**

S. Krinsky, J. Bittner, A.M. Fauchet, E.D. Johnson,
J. Keane, J. Murphy, R.J. Nawrocky, J. Rogers,
O.V. Singh and L.H. Yu

September 1991

NATIONAL SYNCHROTRON LIGHT SOURCE

**BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.**

Under Contract No. DE-AC02-76CH00016 with the

UNITED STATES DEPARTMENT OF ENERGY

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DE92 002064

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MASTER

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1 INTRODUCTION

1.1 The NSLS Facility

Research utilizing synchrotron radiation was initially carried out parasitically on synchrotrons and storage rings designed and operated for high energy physics. The National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory was one of the first facilities developed as a dedicated synchrotron radiation source. The NSLS began in 1977 as a 24M\$ construction project, and later a 20M\$ Phase II upgrade program was carried out providing state-of-the-art insertion device sources, experimental beamlines, and a much needed expansion of the building. There are presently 85 operating beamlines out of a full capacity of 98. Operating 7 days/week 24 hours/day, the NSLS has 65% of the calendar year scheduled for user beam, 15% for machine studies and 20% for maintenance. During FY 1990, more than 1800 users representing 292 organizations carried out experiments at the NSLS. The user community is comprised of 62% university, 19% corporate, 16% national laboratory researchers, and 3% other (e.g. high school students). The NSLS facility provides its users with photons, establishes safety and technical standards, and provides oversight and support. A majority of the experimental programs at the NSLS are run by Participating Research Teams (PRT) with diverse membership and funding sources. These PRTs establish their own scientific goals, carry out the technical design of their experiments, and construct and maintain their own equipment. A PRT schedules 75% of its beamtime for its own program, while the other 25% is allocated to outside general users by a procedure overseen by the NSLS management. The PRT system has allowed enormous resources from outside DOE to be applied to the usage of the NSLS. Users may carry out proprietary research at the NSLS although in this case the facility receives compensation at a rate corresponding to full cost recovery.

The NSLS facility (Fig. 1.1) is comprised of an 80 MeV electron linac which injects into a small (28-m circumference) booster synchrotron [1.1] which accelerates the electrons up to 750 MeV. The booster serves as a full energy injector for the VUV storage ring [1.2], which operates at 750 MeV to provide radiation in the ultraviolet and soft X-ray regions of the spectrum. The booster also is used to inject electrons into the X-ray storage ring [1.3] which operates at 2.5 GeV providing hard X-rays.

Fig. 1.1 The NSLS Facility

Based upon the work of G.K. Green and R. Chasman the NSLS storage rings were designed to maximize the brightness of the synchrotron radiation source, i.e. maximize photons/sec/phase-space volume/unit bandwidth. The fundamental importance of brightness as a figure of merit of the radiation source is that brightness is left invariant by linear focusing optics. The photon beam can be focussed to a small spot size at the expense of introducing a large angular divergence, or can be made very parallel at the expense of increasing the spot size. However, if an experiment requires an intense highly parallel photon beam incident on a small sample, then a high brightness source is required.

In order to provide a high source brightness [1.4], the NSLS storage rings were designed to have small emittance. This was accomplished by using the "Chasman-Green" lattice design [1.5] which utilizes achromatic bends with zero-dispersion insertions bounded by quadrupole doublets in the VUV ring and quadrupole triplets in the X-ray ring. The lattice functions for the VUV and X-ray rings are given in Figs. 1.2 and 1.3, and some of the storage ring parameters are presented in Table 1.1.

Fig. 1.2
Lattice Functions for VUV-Ring

$$\begin{aligned}
 E &= 0.744 & \alpha &= .235E-01 \\
 N_p &= 4 & \epsilon &= .138E-06 \\
 \nu_x &= 3.123 & \xi_x &= -3.50 \\
 \nu_y &= 1.179 & \xi_y &= -5.00
 \end{aligned}$$

Fig. 1.3
Lattice Functions for X-Ray Ring

$$\begin{aligned}
 E &= 2.500 & \alpha &= .854E-02 \\
 N_p &= 8 & \epsilon &= .102E-06 \\
 \nu_x &= 9.144 & \xi_x &= -22.37 \\
 \nu_y &= 6.202 & \xi_y &= -18.50
 \end{aligned}$$

Table 1.1 NSLS Storage Rings

	X-RAY RING	VUV RING
Energy	2.5 GeV	0.75 GeV
λ_c	2.5 Å	25 Å
Current	240 ma	800 ma
Lifetime	40 hrs. (gas scattering)	2-4 hrs. (Touschek scattering)
Emittance ϵ_x ϵ_y	10^{-7} m-rad 10^{-9} m-rad	1.5×10^{-7} m-rad 1.5×10^{-9} m-rad
Typical Beam size σ_x σ_y	0.35 mm 0.12 mm	0.40 mm 0.15 mm

Synchrotron radiation sources are important to the scientific community due to their unique properties. They are, in fact, the most versatile of EM sources, offering

- High Intensity Over Broad Spectral Range
- High Brightness
- Small Angular Divergence
- Small Source Size
- Temporal Coherence (Tunable Wavelength Utilizing Monochromator)
- Spatial Coherence (Pinhole as Spatial Filter)
- Pulsed Time Structure
- Polarization

High intensity and high brightness have been of central importance to the development of high resolution instruments for the study of small samples, surfaces and interfaces. The broad spectrum of synchrotron radiation has allowed the development of extremely diverse experimental programs utilizing the same facility.

High temporal coherence is achieved with monochromators utilizing crystals (X-rays), gratings (ultraviolet) and interferometers (infrared). The ability to continuously tune the wavelength at the experiment using monochromators has opened up new scientific opportunities not possible using conventional line sources. Experiments requiring spatial coherence have been carried out using a pinhole as a spatial filter. In this manner holograms have been recorded at 30Å. High intensity together with the pulsed time structure of the radiation allows the study of time-dependent phenomena in physical and biological systems. The polarization of the source is employed in the study of magnetic systems and in investigations of the dichroism of large helical molecules.

As an example of an experiment requiring high source brightness, let us consider focusing the source to a small diffraction limited spot. See Fig. 1.4. For a given source size S , the acceptance angle for coherent illumination of the lens is Θ_{ACC} determined by

$$S\Theta_{ACC} \leq \lambda, \quad (1.1)$$

where λ is the wavelength of the radiation. The diffraction-limited spot size is given by

$$R_{min} = \frac{\lambda}{\sin\alpha} \quad (1.2)$$

where α is the angle defined in Fig. 1.4. For a given source size S , illuminating the lens by radiation emitted into an angle larger than Θ_{ACC} does not help, since in this case the lens will no longer be coherently illuminated and the achievable spot size will be increased over the diffraction limited value R_{min} , resulting in a loss of spatial resolution. Therefore, the figure of merit is the source brightness, i.e. the number of photons emitted per sec, per unit source area, per unit solid angle, per unit spectral bandwidth $\Delta\lambda/\lambda$.

Fig. 1.4 Source of full width S focused to diffraction-limited spot of full width R

The scientific program at the NSLS is too broad to be described here, however, it seems worthwhile to provide some examples of work being done. The work on sub-micron X-ray lithography carried out by IBM and more recently by AT&T Bell Laboratories has received much attention, and is critical to the development of the computing capability fundamental to all basic and applied sciences. Many research groups have been working on the high- T_c superconductors, whose remarkable properties and potential impact on society have created great excitement. Exxon has developed a technique of X-ray microtomography which provides non-invasive 3-D images of the internal structure of small samples with micron resolution. A picture taken by this group of Illinois No. 6 coal appeared on the cover of *Science* (September 1987) showing iron and sulfur components. Of the many types of surface science research pursued by users of the NSLS, fundamental catalysis studies are a major focus for many groups. For example zeolites, which are aluminosilicate materials, have been the subject of intense investigations which attempt to relate the structure of these materials to their chemical function. Other work using an X-ray microprobe allows trace element analysis of ores, with the goal of understanding the geological processes in the strata where they were located. There are also investigations of the properties of small atomic clusters, related to the combustion processes.

A new and potentially important use of synchrotron radiation is in medical science. Human coronary angiography has been carried out by injecting iodine into a vein rather than an artery as is the case for conventional techniques, resulting in a dramatic decrease in risk. By using a differential technique subtracting the transmitted intensity above and below the iodine K-edge (33 KeV), clear images of the arteries are obtained unobscured by bone or other tissues, providing a valuable diagnostic tool. Another application in the life sciences is the scanning soft X-ray microscope. Using radiation at the carbon or nitrogen edges, for which water is transparent, images of living (or dying) cells in vitro can be made with sub-micron resolution. Electron microscopy can be applied only to dehydrated cells. Of course, the use of X-rays to determine the structure of macromolecules important in biology is also of great importance.

An outline of some areas of science pursued at the NSLS is presented in Table 1.2.

Table 1.2 Science at the NSLS

<u>Surfaces and Interfaces</u>
Structure, phase transitions, band structure, MBE growth
<u>Imaging</u>
Angiography, lithography, microtomography, topography, photoemission and scanning microscopy
<u>Magnetism</u>
Faraday effect, dichroism, reflectivity, spin polarized photoemission, resonant and non-resonant scattering

1.2 Insertion Device Sources

Most of the beamlines at the NSLS use radiation emitted by the electrons passing through the storage ring bending magnets. Special sources with enhanced intensity and brightness relative to the bending magnet sources are available from wiggler and undulator magnets situated in the storage ring straight sections [1.6-1.8]. The axis of the wiggler magnet is parallel to the unperturbed electron motion (z-direction), and it produces a vertical magnetic field B_y alternating in polarity with period length λ_w in the z-direction, and to good approximation the field is sinusoidal,

$$B_y = B_w \sin(2\pi z / \lambda_w). \quad (1.3)$$

The magnetic field causes an electron to be deflected in the horizontal plane and we denote this deflection x . Measured in units of its rest mass, the electron has energy γ , and we let ρ_w denote the radius of curvature corresponding to the peak field B_w . The angular deflection, $x' = dx/dz$, of the electron is

$$x' = \delta \cos(2\pi z / \lambda_w), \quad (1.4)$$

where the maximum angular deflection δ is given by

$$\delta = \lambda_w / 2\pi \rho_w, \quad (1.5)$$

and the amplitude of the transverse oscillation is $\rho_w \delta^2$. The magnitude of the electron velocity divided by the speed of light is denoted $\beta = \sqrt{1 - \gamma^{-2}}$. Due to the transverse

deflection, the average velocity β^* in the z-direction is reduced from the value β , and is approximately

$$\beta^* = \beta(1 - \delta^2/4). \quad (1.6)$$

If we consider the wavefront radiated in the z-direction by an electron passing through the periodic magnetic field, time λ_w/β^*c later, the electron has passed through one period of the magnet, and a second wavefront emitted at this time will follow the first by a time interval

$$T_1 = \lambda_w/\beta^*c - \lambda_w/c. \quad (1.7)$$

An observer downstream of the magnet looking in the forward direction sees a radiation spectrum comprised of the fundamental frequency $\omega_1 = 2\pi/T_1$ and its odd harmonics $\omega_k = k\omega_1 (k=1,3,5,\dots)$. Defining

$$K = \gamma\delta \approx 0.93B_w(T)\lambda_w(\text{cm}), \quad (1.8)$$

the fundamental wavelength $\lambda_1 = cT_1$ can be expressed as

$$\lambda_1 = (\lambda_w/2\gamma^2)(1 + K^2/2). \quad (1.9)$$

If an observer is looking at radiation emitted at a polar angle θ relative to the z-axis, then the time delay between wavefronts emitted before and after an electron has traversed one period of the magnetic field is

$$T_1(\theta) = \lambda_w/\beta^*c - \lambda_w \cos\theta/c, \quad (1.10)$$

as illustrated in Fig. 1.5. One should not interpret Fig. 1.5 as describing spatial interference, but rather temporal coherence, i.e. a regularity in the time dependence of the electric field. Off the forward direction the radiation spectrum is comprised of both odd and even harmonics of the fundamental frequency. The fundamental wavelength is

$$\lambda_1(\theta) = (\lambda_w/2\gamma^2)(1 + K^2/2 + \gamma^2\theta^2). \quad (1.11)$$

Fig. 1.5 Path length difference vs. observation angle θ

For a magnet with N periods, the radiated pulse from one electron passing through the device has a time duration of NT_1 , hence the pulse contains Nk radiation periods at the k th harmonic frequency ω_k . Consequently, the line width at fixed observation angle θ is

$$\Delta\omega_k/\omega_k \approx 1/kN. \quad (1.12)$$

Due to the dependence of the frequency on observation angle, if the observer accepts radiation in an interval $\Delta\theta$, then the width of the line is broadened relative to its natural value (Eq. (1.12)). From Eq. (1.11), we see that the angular broadening due to accepting radiation in a cone of half-angle $\Delta\theta$ about the forward direction is $\Delta\omega_k/\omega_k = \gamma^2(\Delta\theta)^2/(1+K^2/2)$. This broadening will be small only if

$$\Delta\theta < \sigma'_R \quad (1.13)$$

where we define

$$\gamma\sigma'_R = \sqrt{(1+K^2/2)/2kN}. \quad (1.14)$$

In the forward direction, radiation from a wiggler is in general characterized by *two time scales*. The first is the time interval T_1 already discussed in Eq. (1.7), and the second is the time T_c characteristic of synchrotron radiation,

$$T_c = \frac{4\pi\rho_w}{3c\gamma^3}.$$

Fig. 1.6 Electric field vs. time for (a) wiggler, $K \gg 1$ and (b) undulator $K \approx 1$

When the magnetic strength parameter $K \gg 1$, then $T_1 \gg T_c$, and the time dependence of the radiated electric field has the form illustrated in Fig. 1.6a. For high harmonic number k , the frequency spectrum is characterized by the synchrotron radiation cutoff frequency $\omega_c = 2\pi/T_c$. The radiation in the regime of $K \gg 1$ has the spectral properties of normal synchrotron radiation from a bending magnet and is called *wiggler* radiation.

When the field strength parameter $K \leq 1$, then $T_1 \leq T_c$, and the time scale T_c characteristic of synchrotron radiation drops out of the problem. In this case one usually speaks of *undulator* radiation. From Eq. (1.8) it is seen that undulator radiation is produced by devices which have short periods and low fields. For an undulator with $K = 1$, the time dependence of the electric field in the forward direction has the form illustrated in Fig. 1.6b. For $K \ll 1$, the electric field has almost a purely sinusoidal time dependence and hence the radiated spectrum is dominated by the line at the fundamental frequency ω_1 . When K increases toward unity, the third-harmonic becomes important, corresponding in the time domain to a sharpening of the peak of the electric field. As K increases toward even higher values, the higher harmonics increase, corresponding to well-defined pulses of width T_c separated by the time T_1 , as in Fig. 1.6a. Even for large values of K , however, temporal coherence effects are still significant for the lowest harmonics.

It is worth noting that σ_R' defined in Eq. (1.14) can be equivalently expressed as

$$\sigma_R' = \sqrt{\lambda_k/L} , \quad (1.15)$$

where $\lambda_k = \lambda_1/k$ is the wavelength of the k th harmonic, and $L = N\lambda_w$ is the undulator length. The angular spread of the electron beam passing through the undulator is

$$\sigma_{x,y}' = \sqrt{e_{x,y}/\beta_{x,y}} . \quad (1.16)$$

When $\sigma_{x,y}' \lesssim \sigma_R'$, then the radiated wavelength λ is correlated with observation angle as described in Eq. (1.11). The bandwidth $\Delta\lambda/\lambda$ is on the order of that given in Eq. (1.12), and hence certain experiments not requiring very narrow bandwidths can benefit from the elimination of the need for a monochromator. On the other hand, if the undulator is operated in an insertion having smaller $\beta_{x,y}^*$ such that the angular spread of the electron beam passing through the undulator is on the order of $1/\gamma$ (as is the case in the X-ray ring), then the radiated wavelength is not correlated with the observation angle. The spectrum seen by an observer accepting radiation into only a very small solid angle will be proportional to a partially angle-integrated spectrum, since the spread in directions of the average velocity vectors of the different electrons produces essentially the same effect as does a spread in observation angles. One can still take advantage of the high brightness by using a monochromator. Let us emphasize that in this case there will be intense radiation at the even as well as the odd harmonics. Utilization of the even harmonics can be important, as is the case for the experimental program using the soft X-ray undulator at X1 on the X-ray ring, which uses the second as well as the first harmonic.

The NSLS storage rings have specially designed zero-dispersion insertions for the placement of wigglers and undulators. In the VUV ring the beta functions at the insertion center have the values $\beta_x=11$ m, $\beta_y=6$ m resulting in relatively small angular spread of the electron beam. On the other hand, in the X-ray ring the beta functions at the insertion center are quite small, $\beta_x=1.5$ m, $\beta_y=0.33$ m, resulting in very small transverse electron beam dimensions, but somewhat larger angular spread. Some advantages of low- β insertions are: the effect of the wiggler magnetic fields on the lattice are minimized, the brightness is optimized for short high-field wigglers, and the low vertical beta function allows the development of very small gap devices situated at the insertion center. An important disadvantage of low- β insertions is that orbit variations can result in large vertical angular deviations which could illuminate uncooled portions of the vacuum chamber with high power wiggler radiation. For this reason it has been necessary to develop special active interlock systems for the X-ray ring which use pick-up electrodes on either end of the straight section to detect orbit motion and to dump the electron beam if orbit movements are too large (see Section 8).

In Table 1.3, we present the basic parameters of the insertion devices [1.8] for the NSLS storage rings, and in Table 1.4, we give an indication of the nature of the scientific program utilizing the experimental beamlines. In Fig. 1.7, the brightness of the insertion devices is plotted against photon energy. We see that the parameters of the insertion devices were chosen to offer enhanced photon sources over the broad photon energy range from 10 eV to 100 KeV. There are two additional state-of-the-art sources which lie outside this spectral range. One is an infrared beamline [1.9], IR4, situated on the VUV ring, providing a continuously tunable, high brightness, low-noise source in the wavelength region from 10 μ m to 1000 μ m. The other is a Compton backscattering source (LEGS) [1.10] on the X-ray ring, yielding 300 MeV gamma rays for nuclear physics experiments.

Table 1.3 Parameters for the NSLS Insertion Devices

Parameters	U5U	U13TOK	X1	X13	X17	X21/X25
Magnetic Field - B_{max}	0.46-0.01T	0.72-0.05T	0.31-0.03T	0.31-0.03T	5 poles @ 5.2T 2 poles @ 2.6T	1.1T
Number of Poles - N	55	44	69	20	7	27
Period Length - λ_w	7.5 cm	10 cm	8 cm	8 cm	17.4 cm	12 cm
Wiggler Characteristic Energy - E_c	--	265 eV	--	--	22.2 keV (for 5.2T poles)	4.57 keV
Energy Range (Undulator Fund.)	11.3-70 eV	2.2-50 eV	0.19-0.73 keV	0.19-0.73 keV	10-100 keV	4-30 keV
Deflection Parameter Range - K	3.2-0.08	6.7-0.4	2.3-0.2	2.3-0.2	80.9	12.3
Gap Range	3.4-12.0 cm	3.35-12.0 cm	3.3-9.8 cm	3.3-9.8 cm	3.2 cm (fixed)	2.4-12 cm

VUV Ring Energy - 745 MeV; X-Ray Ring Energy = 2.5 GeV

Table 1.4 Insertion Device Beamlines

U5	Spin Dependent Photoemission
U13	Soft X-Ray Spectroscopy
	Projection Lithography
IR4	Infrared Spectroscopy
X1	Soft X-Ray Microscopy
X13	R&D Insertion Device/Instrumentation
X17	High Energy Mat. Science/Medical Research
X21	High E-Resolution X-Ray Scattering
X25	High Q-Resolution X-Ray Scattering
X5	Compton Backscattering (Nuclear Physics)

1.3 Organization of the Paper

In this paper, we shall highlight some of the key on-going activities in the program of storage ring development at the NSLS. A central design feature of the NSLS storage rings is the achievement of small transverse emittance, and in Section 2 a description is given of transverse beam profile monitors utilizing synchrotron radiation. The limitations on resolution are addressed. The longitudinal bunch length is also of interest, especially in the VUV-Ring where the lifetime is determined by Touschek scattering. In Section 3, measurements of the bunch length vs. current in the VUV ring are described, and are shown to be consistent with a Chao-Gareyte scaling law.

Fig. 1.7 Brightness of NSLS sources as function of photon energy with current of 800 ma in VUV-Ring and 250 ma in X-Ray Ring

The single most critical issue in the development of the NSLS storage rings is the improvement of the stability and control of the operating electron beam orbit. In Section 4, a discussion is presented of photoelectric effect position monitors utilizing the synchrotron radiation to determine the movement of the electron beam. Next, in Section 5, RF receivers for processing electron beam pick-up electrode signals are described. These receivers are central to our program of orbit control and are utilized to provide electron beam position data for both local and global orbit feedback systems.

In Section 6 we outline the design of a global orbit feedback system based upon harmonic analysis of the orbit variations, and in Section 7 we present the fundamental design features of local orbit feedback systems. The RF receivers are also used in the active interlock systems to protect uncooled portions of the vacuum chamber from being illuminated by the high power insertion devices. These active interlock systems are discussed in Section 8.

As mentioned earlier, the lifetime in the VUV ring is determined by Touschek scattering within a bunch. The lifetime is therefore inversely proportional to the electron bunch density. In order to maintain a bright source, it is desired to keep the transverse bunch dimensions small. Therefore, to increase the lifetime we have been led to increase the bunch length by using a fourth-harmonic 211 MHz RF cavity. The development and operation of the bunch lengthening cavity is described in Section 9.

The paper is concluded in Section 10 with a discussion of the development at the NSLS of a compact superconducting storage ring (SXLS) specifically designed to serve as a source for X-ray lithography. In particular, the SXLS storage ring optics and the tracking studies determining the dynamic aperture are presented.

Acknowledgement

We would like to take this opportunity to thank John Galayda for his fundamental contributions to the storage ring development at the NSLS. The work reported in this paper is broad in scope, but it has all benefitted from John's technical insight and leadership.

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2 TRANSVERSE BEAM PROFILE MONITOR

2.1 Introduction

During the commissioning and operation of an electron storage ring it is useful to be able to measure the transverse profile of the electron beam. The vertical and horizontal beam sizes yield information about the beta functions and emittance. The vertical size and the skewness of the beam profile are measures of the horizontal-vertical coupling. Transverse instabilities can be observed as they occur even if they have no dipole moment and go undetected by pickup electrodes or striplines, and ion trapping is easily detected as a vertical expansion of the beam.

A non-destructive way of determining the beam profile is by imaging the synchrotron radiation produced in the bending magnets. The optical intensity of the profile in the image plane is proportional to the electron density in the source plane. Several means of producing an image are possible, including using zone plates or curved grazing-incidence mirrors to focus X-rays; pinholes to collimate X-rays; or lenses to focus visible light. The last two methods are the simplest and we will describe them in more detail.

The characteristic wavelength of the radiation from a bending magnet is [2.1]

$$\lambda_c = 4\pi \frac{\rho}{3\gamma^3} \quad (2.1)$$

where ρ is the orbit radius. The power radiated per radian of orbit is (in MKSA units)

$$P_o = \frac{2}{3} \frac{e}{4\pi\epsilon_0} \frac{I\gamma^4}{\rho} \quad (2.2)$$

where I is the beam current. The angular distribution of the radiation is sharply peaked in the direction of the electron's motion, with a horizontal and vertical width of

$$\sigma_R \approx \frac{1}{\gamma} \left(\frac{\lambda}{\lambda_c} \right)^{1/3} \quad (2.3)$$

at and above the characteristic wavelength. Right away we can see that increasing the aperture of the imaging system beyond the width of the radiation fan won't help to sharpen the image; there is a kind of natural diffraction limit from Eq. (2.3). Imaging the shorter wavelengths leads to a better diffraction limit, but that advantage is countered by the practical difficulty of making X-ray focussing optics.

Fig. 2.1 Geometry of synchrotron radiation emission.

2.2 Visible Synchrotron Light Imaging

To image the beam using visible synchrotron light [2.2, 2.3], the simplest arrangement is to use a lens. The synchrotron light accepted by the aperture of the lens comes from an arc along the electron orbit, as shown in Fig. 2.1. If the aperture is made larger, the arc is longer and there is a transverse blurring of the focussed image. The apparent horizontal source width is approximately

$$\Delta x = \frac{\rho \theta^2}{8} \quad (2.4)$$

where θ is the angular acceptance of the aperture. If the aperture is made smaller, blurring of the image by diffraction becomes worse. The apparent widening of the source due to diffraction is

$$\delta x = \frac{\lambda}{\theta} \quad (2.5)$$

The optimum aperture width is found by minimizing the quadrature sum of these two widths:

$$\hat{\theta} = 2\left(\frac{\lambda}{\rho}\right)^{1/3} \quad (2.6)$$

Another argument leads to a very similar conclusion. There is a natural diffraction limit imposed by the angular width of the emitted radiation, given by Eq. (2.3). The aperture should be no smaller than this, but no larger either, as the diffraction limit

will not improve but the apparent horizontal source size will increase. The optimum aperture is then approximately $2\sigma_R$. From Eqs. (2.1) and (2.3),

$$2\sigma_R = 2\left(\frac{3}{4\pi}\right)^{1/3}\left(\frac{\lambda}{\rho}\right)^{1/3} \quad (2.7)$$

which is nearly the same aperture determined in Eq. (2.6). The resolution of the source is approximately

$$[(\Delta x)^2 + (\delta x)^2]^{1/2} = \frac{1}{\sqrt{2}}(\lambda^2 \rho)^{1/3} . \quad (2.8)$$

For the monitor to be useful this resolution must be less than the transverse size of the beam.

Several important practical considerations influence the design of such a monitor. For actual synchrotron light sources, the radiation power accepted by the aperture is in the range of 10 to 1000 watts, mostly in X-rays. Transparent optical materials such as glass tend to be damaged by the radiation and darken over time. A metal mirror can be used to reflect the visible light to the lenses while absorbing the X-rays. However, the power absorbed by the mirror may heat it enough to create a local expansion that distorts the image, so the cooling geometry is critical.

An example of a visible-light monitor is the U5 monitor on the NSLS VUV ring [2.2]. Figure 2.2 shows the optical arrangement. A mirror is used to reflect the visible light vertically up over the shielding wall. A fused silica window transmits the light from machine vacuum to the air.

A single lens forms the image at unity magnification. Just before the lens, 194 cm from the source, is an aperture 2 cm on a side, admitting 10.3 milliradians vertically and horizontally. The 2σ width of the radiation cone, from Eq. (2.3), is 7 mrad. The calculated 1σ resolution of 23 microns for 400-nm light is dominated by diffraction. A bandpass filter centered at 400 nm with a width of 30 nm

Fig. 2.2 The NSLS U5 visible-light monitor.

eliminates the long-wavelength light which would degrade the diffraction limit and reduces the chromatic aberration.

The imaging devices are Reticon linear photodiode arrays [2.4]. These are self-scanning silicon devices that provide an output voltage proportional to the intensity of the incident light. A feedback loop controlling the clock frequency, shown in Fig. 2.3, insures that the peak of the output signal remains constant regardless of light intensity, which varies with beam current. Two photodiode arrays are used, one each for the vertical and horizontal profile. A pellicle beamsplitter splits the focussed light for use by both arrays. Positive cylindrical lenses are mounted on the arrays to integrate the light over the unresolved direction.

Fig. 2.3 Scanning electronics for linear photodiode arrays.

The measured horizontal and vertical profiles are shown in Fig. 2.4. The beam size in both dimensions is larger than the calculated resolution, and larger than the 25- μm spacing between adjacent photodiode elements, showing that the resolution is adequate. This monitor has been in regular use at the NSLS for 5 years. Silicon area detectors are also commercially available, and this monitor will be upgraded with the addition of a charge-coupled-device (CCD) camera, which allows the skewness of the image to be seen.

Fig. 2.4 Measured vertical and horizontal beam profiles from the NSLS U5 visible light monitor (left). The trace on the right is the vertical profile with an expanded length scale.

2.3 X-Ray Synchrotron Light Imaging with a Pinhole Collimator

An alternative way to image the beam is to use a pinhole collimator to define the path of the synchrotron light [2.5]. In this case, visible light can't be used because the diffraction limit (Eq. 2.5) would be so poor. This method is ideally suited to X-rays instead, because of their short wavelength and the difficulty of making focussing X-ray optical elements.

A pinhole camera monitor is illustrated in Fig. 2.5. The imaging property of the pinhole is purely geometrical. Rays falling on the image plane must have passed through the small aperture of the pinhole, and so form an inverted image of the source. Because the pinhole has a finite width, there will be a purely geometrical blurring of the image of a point source with variance

$$\sigma_s = \frac{D}{4} \frac{S_i + S_s}{S_s} \quad (2.9)$$

Fig. 2.5

Imaging geometry of a pinhole camera monitor.

for a circular pinhole of diameter D , with source-pinhole and pinhole-image distances S_s and S_i . The diffraction blurring of the image from such a pinhole is

$$\sigma_d = \frac{1.22}{2\sqrt{2\ln 2}} \frac{\lambda S_i}{D} \quad (2.10)$$

The blurring due to the finite arc length of the source, which was a concern for the visible-light monitor, is negligible here because of the small pinhole aperture. Adding Eqs. (2.9) and (2.10) in quadrature yields the image size. Minimizing this size with respect to D gives an optimum pinhole diameter

$$D_{opt} = \left(\frac{2.07 \lambda S_i S_s}{S_i + S_s} \right)^{1/2} \quad (2.11)$$

for which the image resolution is

$$\sigma_i = \left(\frac{.259 \lambda S_i (S_i + S_s)}{S_s} \right)^{1/2} . \quad (2.12)$$

The equivalent equations for a square pinhole W on a side are

$$\sigma_s = \frac{W}{2\sqrt{3}} \frac{S_i + S_s}{S_s} , \quad (2.13)$$

$$\sigma_d = \frac{.866}{2\sqrt{2\ln 2}} \frac{\lambda S_i}{W} , \quad (2.14)$$

$$W_{opt} = \left(\frac{1.27 \lambda S_i S_s}{S_i + S_s} \right)^{1/2} , \quad (2.15)$$

$$\sigma_i = \left(\frac{.212 \lambda S_i (S_i + S_s)}{S_s} \right)^{1/2} . \quad (2.16)$$

The practical difficulties encountered in constructing an X-ray pinhole collimator are different from the case of the visible-light monitor. Radiation damage and thermal distortion of the imaging elements are no longer concerns. However, the pinhole must be much thicker than its width to block the hard radiation, making it difficult to manufacture and align. In addition, the radiation cone is narrower at short wavelengths, so that beam movement may make the X-rays miss the pinhole entirely. Also, the imager used must be radiation-hard.

As an example we use a design study for a pinhole camera to be built on the NSLS X-ray ring. Here the critical wavelength, which we'll use to calculate diffraction blurring, is 2.4 Å. The source-pinhole and pinhole-image distance are both 8 m, resulting in unity magnification. A square pinhole, constructed of two crossed slits, was chosen for ease of manufacture. The optimum width, from Eq. (2.15), is 35 μm , leading to a resolution of $\sigma_i = 29 \mu\text{m}$.

A high-Z material, in this case tantalum, is used to make the pinhole as opaque as possible. The tantalum slits are each 1.6 mm thick. The absorption length reaches a local maximum just under the 67-keV Ta K edge, where it is $1/\mu = 2.2 \times 10^{-2} \text{ cm}$ [2.6]. Above this energy the synchrotron spectrum falls off very rapidly. By using a thick copper precollimator with a 1.6-mm-diameter opening, the flux through the tantalum is made less than 10^{-4} of the flux through the pinhole aperture. Such a long, thin pinhole has an angular acceptance of only 44 mrad, which admits all of the light from the beam, but requires care in alignment.

The pinhole assembly absorbs 80 watts of radiation, which is carried away by cooling water. The expansion of the pinhole support, which would be confused with beam movement, is minimized by a high flow rate and the choice of low thermal expansion support materials. Long-wavelength radiation, which would worsen the diffraction limit, is eliminated by using a beryllium filter after the pinhole.

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3 BUNCH LENGTH MEASUREMENTS IN THE VUV STORAGE RING

3.1 Introduction

Measurements of the bunch length have been made as part of a study of current-dependent phenomena to provide a complete characterization of the VUV ring. Scaling laws have been put forth for the anomalous bunch lengthening with current which is generally observed in storage rings [3.1, 3.2]. However, there is no complete theory of the lengthening phenomenon and it is of great interest to compare the behavior of existing machines to the scaling laws. In addition, high peak currents are sought both for damping rings for linear colliders and for free-electron laser drivers and might be achieved through low-momentum compaction lattices. Finally since the bunch lengthening depends on the vacuum chamber impedance it should be remeasured after each significant modification of the vacuum chamber. The accepted scaling law of bunch length with current contains the RF voltage, electron energy and momentum compaction. The VUV ring was particularly interesting for such measurements because we could separately and easily vary both the electron energy and the momentum compaction. Although the ring is injected at full energy (750 MeV) we have had extensive experience running the ring at low-energy (as low as 80 MeV) for the TOK project. Experimental studies of a low-momentum compaction lattice were started following an ICFA workshop at BNL. In addition the ring operates over a large current range in a single bunch above the turbulent bunch lengthening threshold allowing us to hope to check the scaling law over as much as 3 decades of charge per bunch.

In the following we discuss our measurement technique. The low current bunch length in operational conditions is on the order of 170 psec (σ), i.e., comparable to or longer than the vacuum pipe's smallest dimension, and allows a simple measurement. We present data of bunch length versus current (up to 500 mA in a single bunch), varying electron energy and momentum compaction. Finally, a fit of the data with the Chao-Gareyte model [3.1] is discussed.

3.2 Measurement Technique

Choice of the measurement method depends on the expected bunch length, on whether one absolutely has to have single-shot measurements or whether one can accept an average measurement and on the money available since measurement of very short bunches does require expensive equipment. There are 2 classes of measurement techniques: one based on the electrical signal induced by the electron beam on a broadband electrical pick-up (a stripline for example), the other on measuring the length of the synchrotron radiation pulse emitted in a bending magnet or an insertion. Processing of the pick-up signal or the photoelectron current can be done with various techniques: single-shot measurements or techniques which average over many electron pulses.

Let us first discuss detectors. Electrical signal measurements require knowing and deconvoluting the stripline or pick-up electrode frequency response or time

response depending on the choice of processing in the time or frequency domain. The bunch length dictates the bandwidth necessary from the pick-up electrode or stripline. Light detectors allow use of all techniques developed for lasers. One has the choice between solid-state detectors or vacuum diodes. At the time of the measurements cited, a 15-psec-risetime silicon detector was available but it had an extremely small active area, below a square mm, making it very difficult to align. This has been a problem with solid-state detectors so far. Fast vacuum diodes (about 50 psec risetime) are available with active areas on the order of 1 cm diameter, thus very comfortable. A vacuum diode is essentially the first stage of a photomultiplier tube.

For the processing of the electrical signal one can: (1) Use an oscilloscope: one is limited by the 1 GHz of commonly available analog or digital oscilloscopes. Analog oscilloscopes up to 6 GHz have appeared since our measurements were done and there is even a very expensive 70-GHz system. (2) Use an electrical sampling technique, which gives an average measurement. (3) Process the signal in the frequency domain, which can be complicated especially for a non-Gaussian bunch shape and also gives an average quantity. Shorter bunches do require the use of a streak camera, and we had such a detector available for a few hours. We were thus able to make single shot measurements. Streak cameras are still however quite expensive, especially for such limited use as bunch length measurement. Autocorrelation techniques, similar to those used in lasers, are starting to be introduced [3.3].

The expected bunch length in the VUV Ring (σ_L on the order of 100 psec) allowed us to use a very simple measurement technique. We detected the synchrotron radiation light with a vacuum photodiode (Hamamatsu model R1328U.02) in the visible part of the spectrum. The electrical signal coming out of the photodiode was processed with a sampling oscilloscope (Tektronix sampling head S-4, used with an extender, trigger recognizer S53, sampler 7S2 and Tektronix mainframe 7603). Pictures of the oscilloscope trace were taken and the full width at half-maximum measured, assuming a Gaussian pulse. The risetime of the vacuum photodiode plus sampling unit was estimated to be 66 psec from manufacturer specifications. This figure was confirmed by measuring the response of the diode and sampling unit to the 2 to 3-psec-long laser pulse emitted by a synchronously pumped dye laser oscillator. The laser pulse length was known from measurements employing an autocorrelation technique.

3.3 Data

Since the VUV ring is a small and simple machine (see Table 3.1 for storage ring parameters) it was easy to change both the electron energy and the momentum compaction. The electron energy was changed keeping the same lattice. Energy ramps for the nominal lattice were preexisting. Figure 1.2 shows the VUV ring lattice functions. The momentum compaction was changed while keeping the tunes constant by letting the dispersion become non-zero in the straight sections, as shown in Fig. 3.1. The data presented here were taken mid-1987. Figure 3.2 shows the bunch length σ_L versus current per bunch at various electron energies for the nominal momentum compaction of 0.0235 (data sets B,C,D), and at a momentum compaction

Table 3.1

VUV Storage Ring Parameters as of January 1991	
Parameters	VUV Storage Ring
Normal Operating Energy	0.745 GeV
Maximum Operating Current (multibunch operation)	1.0 amp ($1.1 \times 10^{12} e^-$)
Circumference	51.0 meters
Number of Beam Ports on Dipoles	17
Number of Insertion Devices	2
Maximum Length of Insertion Devices	~2.5 meters
$\lambda_c(E_c)$	25.3 Å (486 eV)
$B(\rho)$	1.28 Tesla (1.91 meters)
Electron Orbital Period	170.2 nanoseconds
Damping Times	$\tau_x \equiv \tau_y \equiv 17$ msec; $\tau_z \equiv 9$ msec
Touschek lifetime dependent on current per bunch and vertical emittance	200 min @ 200 mA
Lattice Structure (Chasman-Green)	Separated Function, Quad, Doublets
Number of Superperiods	4
Magnet Complement	8 Bending (1.5 meters each) 24 Quadrupole (0.3 meters each) 12 Sextupole (0.2 meters each)
Nominal Tunes ν_x, ν_y	3.14, 1.20
Momentum Compaction	0.023
R F Frequency	52.887 MHz
Radiated Power	14.7 kW/amp of Beam
R F Peak Voltage (typical)	100 kV
Design R F Power	50 kW
ν_s (Synchrotron Tune)	0.002
Natural Energy Spread (σ_E/E) **	4.5×10^{-4} ($I < 20$ mA)
Natural Bunch Length (2σ) **	7.6 cm ($I < 20$ mA)
Number of RF Buckets	9
Typical Bunch Mode	7
Horizontal Damped Emittance (ϵ_x)	1.5×10^{-7} meter-radian
Vertical Damped Emittance (ϵ_y)	$\geq 2.8 \times 10^{-10}$ meter-radian (adjust.)
Power per Horizontal milliradian, 1A	2.3 Watts
Source Size: σ_h, σ_v	0.5 mm, > 0.06 mm

* Lifetime variable up to ~350 minutes depending on use of bunch lengthening 211 MHz RF cavity.

** Current and RF voltage dependent.

Source of Data: NSLS Parameters, January 1983, compiled by A. van Steenberg; updated values provided by Anne-Marie Fauchet and Norman Fewell (NSLS).

Fig. 3.1 Low Momentum Compaction Optics for the VUV Ring

Fig. 3.2 Bunch Length Versus Current per Bunch, Varying Electron Energy and Momentum Compaction at Constant RF Voltage

of 0.005 for the nominal energy of 745 MeV (data set A). For all these data sets the RF voltage was kept constant at 65.7 kV. For comparison with other machines, 1 A of average current in a single bunch corresponds to a charge per bunch of 10^{12} in the VUV ring. Figure 3.3 shows similar measurements for 3 different values of the momentum compaction, at constant energy and RF voltage.

Fig. 3.3 Bunch Length Versus Current per Bunch, for 3 Different Values of the Momentum Compaction at Constant Energy and RF Voltage

3.4 Data Analysis

To analyze the data, we follow reference 3.1. We assume a coupling impedance:

$$\frac{Z(\omega)}{2\pi R} = Z_0 \omega^4$$

where R is the ring average radius. Defining

$$\xi = \frac{I_{av} \alpha}{v_s^2 E}$$

where I_{av} is the average current in a single bunch, α the momentum compaction, v_s the synchrotron tune and E the electron energy, the bunch length scales as

$$\sigma_z \approx \xi^{\frac{1}{2+\Lambda}}$$

where A is to be fitted. As one can see, we have followed the form derived from the Spear scaling law, allowing for one degree of freedom.

We have used all 7 data sets to fit A above the turbulent bunch lengthening threshold. The scaling law obtained for the VUV ring as of mid-1987 was

$$\sigma_z(\text{ps}) = 0.921 \left[\frac{I(\text{mA})\alpha}{v_s^2 E(\text{GeV})} \right]^{0.411}.$$

The value of A is 0.44. The above formula represents the solid line going through the data points. Some earlier data [3.4] of bunch length versus RF voltage at constant energy and nominal optics gave:

$$\sigma_z = \text{const. } \xi^{0.55}.$$

Some parts of the vacuum chamber (coated ceramics, known to be heating up) were changed however in the interval. Hence, we conclude that the VUV ring does fit a Chao-Gareyte scaling law, over a large range of current values (5 to 500 mA).

Acknowledgements

Many individuals contributed to make these measurements possible, particularly the NSLS diagnostic group. R.R. Freeman from ATT Bell Laboratories, Murray Hill, New Jersey, kindly allowed us the use of a synchronously pumped dye laser oscillator in his laboratory to measure the risetime of our detection system.

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4 PHOTOELECTRIC EFFECT PHOTON BEAM POSITION MONITORS

4.1 Introduction

Stability of the electron orbit is of critical importance at the NSLS. Many experimenters utilizing the NSLS photon beams can take full advantage of the small transverse dimensions of the source only if the electron orbit variation is kept below 10 to 20% of the transverse electron bunch size. Clearly the first step in a program to stabilize the orbit is to develop position monitors with the required sensitivity, reliability and dynamic range. Of great importance are monitors detecting the photon beams themselves, and also monitors measuring the position of the electron beam. In this section we discuss photon beam position monitors utilizing the photoelectric effect, and in the following section the use of capacitively coupled pick-up electrodes to detect electron beam position will be described. Reviews of photon beam position monitoring can be found in Billing [4.1] and Yu [4.2].

We have developed our own photon beam position monitors at the NSLS [4.3, 4.4, 4.5] for use as feedback and diagnostic elements. This work has lead to a better understanding of the operation of existing monitors, and provided us with our own devices for comparison with data provided by users. Presently under development are a family of monitors for use on the beamlines, with the hope that a device which is sufficiently general in design and relatively inexpensive will gain acceptance from both the users and accelerator physicists. The goal of this contribution is to examine two types of photoelectric effect beam position monitors developed at the NSLS, and extract from the discussion the principles which govern their operation and application. These characteristics appear to be quite general and, once recognized, provide a useful guide for understanding the features of many existing beam position monitors.

Perhaps the most important step in any discussion of photon beam position monitors is to define the end objective of the measurement. To date, they have been used for machine diagnostics [4.1, 4.5-4.10], machine feedback detectors [4.2-4.4, 4.9, 4.11-4.13] and as feedback elements in experiments [4.14-4.17]. The characteristics of each application will dictate the types of monitor geometry which can reliably perform the task. This simple (and often ignored) concept is critical to the successful implementation of any photon beam position monitor. Some desirable features are, however, common to all of the above listed applications. The candidate device should be robust, have sensitivity on the order of microns (for present generation sources), be reliable, and have a known and quantified transfer function which should not depend upon the electron beam current.

In what follows we shall proceed to consider two generic types of monitor geometries (1) "Gap monitors," which are designed with the idea that the fringes of the synchrotron radiation will be measured, and the "hot" or fundamental beam will pass through the monitor unimpeded. (2) "Area monitors," which are comprised of two triangular elements nested together similar to the electrodes of a split ion chamber [4.2, 4.11], or the diodes described by Siddons and Kraner [4.16] or Mitsuhashi et al. [4.10].

4.2 Gap Monitors

The simplest and perhaps the most familiar of the gap monitor designs consists of a pair of wires located above and below the center of the photon beam to sense vertical motion, for example see Heald [4.17]. Several implementations utilize blades on edge [4.3,4.4] or at normal incidence [4.18] to the photon beam. The blade designs essentially integrate out to the wings of the beam while the parallel wire monitors sample only a small section of the beam.

If the photon beam is assumed to be Gaussian, and the blades are imagined to be infinitesimally thin (wires), it can be shown analytically [4.19] that the current measured at each blade can be expressed as a function of the distance between the blades G , their displacements $G/2 \pm \delta$ from the beam center, and the width σ of the photon beam Gaussian distribution (see Fig. 4.1).

Fig. 4.1 Schematic side view of a gap-type monitor for sensing vertical beam displacements. The filled circles on the blade edges represent the location of the "wires" described in the text.

The photon beam's vertical intensity distribution is taken to have the Gaussian form

$$I(z) = I_0(t) \frac{1}{\sigma\sqrt{2\pi}} \exp(-z^2/2\sigma^2). \quad (4.1)$$

The photoelectron currents induced on the top and bottom wires are proportional to the incident photon intensities:

$$I_T = I_0(t) \frac{1}{\sigma\sqrt{2\pi}} \exp[-(G/2 + \delta)^2/2\sigma^2], \quad (4.2)$$

and

$$I_B = I_0(t) \frac{1}{\sigma\sqrt{2\pi}} \exp[-(G/2 - \delta)^2/2\sigma^2], \quad (4.3)$$

respectively. The blade currents are typically translated into a position signal by some type of ratio technique to scale out the beam current dependance contained in the total flux $I_o(t)$. One popular method is to take the log of the blade current ratio (LR). For the case of two wires now under discussion, if the displacement is expressed as some fraction of the beam width i.e. $\delta = n\sigma$, the position signal P reduces to :

$$P(LR) = \ln(I_T/I_B) \quad (4.4)$$

$$= -Gn/\sigma. \quad (4.5)$$

An alternative way to derive position information is to compute the difference over the sum (D/S):

$$P(D/S) = \frac{I_T - I_B}{I_T + I_B} \quad (4.6)$$

$$= \frac{\exp(-Gn/2\sigma) - \exp(Gn/2\sigma)}{\exp(-Gn/2\sigma) + \exp(Gn/2\sigma)}. \quad (4.7)$$

The log-ratio method provides an analytical solution linear in displacement, while the difference-over-sum method is only approximately linear over a small range of displacements. Thus, although the log-ratio appears to be the more desirable method of operation, as a practical matter it tends to be quite noisy when the displacements get large. On the other hand, a position derived from the difference-over-sum method saturates in a unique way when the displacement is large and does so in a smooth manner. This is an especially important feature when the monitor system is to be used as a feedback element. It is, however, important to make sure that the sum signal does not get too small or the position signal will become noisy and the advantage of the method will be lost. For the balance of this discussion, position signals will be calculated as D/S.

The next question is how the monitor parameters affect its sensitivity to beam motion. If for the moment we consider the photon beam to have a fixed σ , we can best see the effect by looking at the individual parts of the D/S signal as shown in Figs. 4.2 and 4.3. For "real" blades which integrate the signal out into the wings, it is clear that as the gap gets small with respect to σ the sum signal changes very slowly with displacement. In the limit of zero gap it doesn't change at all. Similarly the difference signal varies more slowly when the gap is small, so one is led to the result that the smaller the gap, the lower the sensitivity to beam displacement. The benefit is an increase in the range of displacement over which the position signal is linear. To first order, one can be traded for the other to suit a particular application. The limitation on the range of trade-off is when shadowing from upstream apertures or low total signal makes the monitor too noisy to use. As a practical matter the blade gap is usually chosen to be 2 to 4 σ .

Fig. 4.2 Schematic view of two monitors with gaps larger and smaller than the beam sigma.

Fig. 4.3 Comparison of the signals for the two monitors in Fig. 4.2. Vertical axis is the normalized signal where S is the sum signal ($T+B$), D is the difference ($T-B$), and P is the position signal (D/S). The horizontal axis is the displacement of the photon beam with respect to the monitor center in units of sigma. The G values in this example are 1 and 5 sigma.

This leads quite naturally to the question of what defines the beam size or σ . Most often, as a first cut, the projection of the critical energy opening angle to the location of the monitor is selected as the design dimension. In the case of photoemission monitors at most synchrotrons in operation today this assumption is generally not true. From the standpoint of the monitor, what matters is the spatial distribution of the radiation in the energy range which produces the photoelectrons, which is usually larger than the $1/\gamma$ opening angle appropriate for photons having the critical energy.

It is important to note that this distribution is a strong function of the material from which the monitor is constructed, and the condition of its surface, since photoemission is essentially a surface effect. Photoyield data [4.20] and methods for calculating absorption spectra [4.21] are available for making estimates of material

properties, but even with high quality vacua, most surfaces tend to become carbon contaminated with time. The steady-state condition of the surface may also be a function of its exposure to the photon beam as demonstrated by Gaupp and Wolf [4.6]. The magnitude of these variations can be as much as 10% in photo-yield on a time scale of a few minutes. The effect seems to be most pronounced in wire type monitors where beam heating of the monitor may be expected to be significant. Variations in the apparent beam size as measured by the monitor will be expressed as changes in monitor sensitivity which should be taken into account when utilizing gap type devices.

Monitors designed for use on undulator beamlines face an additional problem. They must operate in an environment where the actual opening angle of the radiation can change (by changing the insertion device K). For diffraction-limited sources (3rd-generation machines) radiation to which the monitor responds can in fact be somewhat softer radiation off axis [4.22]. To complicate matters further, there can be significant radiation present from the dipoles on either end of the insertion device straight section. Monitors for use in these situations are usually gap type monitors, but have little else in common with the familiar parallel wire configurations.

To deal with the heat load, the monitor elements are cooled and usually designed to minimize the area exposed to the beam. The most common method is to orient the blades with their edge facing the source. The leading edge is most often inclined with respect to the beam axis, which distributes the heat load over a greater length of the blade. This has the additional effect of "hardening up" the response of the monitor and increasing the signal level compared to a normal incidence surface. The reason for the shift of the monitor sensitivity to harder x-rays is that, in the energy range of interest, photons have a much longer mean free path than do photoelectrons.

In this geometry the photons can travel a considerable distance through the blade material while still being absorbed and producing photoelectrons near the surface of the blade. In grazing incidence geometry the sensitivity to the contamination layer on the blade surface is much enhanced. One approach to minimize this problem is to coat the blades with carbon (as graphite), which has properties similar to those of the contaminants that typically build up over time.

Since in insertion devices the flux per solid angle is usually an order of magnitude or more greater than for the adjacent dipoles, narrow monitor blades have the effect of minimizing the signal from bending magnet radiation. The down side of this choice of detector geometry is the possibility of "cross talk" between blades. One could imagine for example a situation where the beam misses one blade completely. This blade would then become an electron collector, and the output of the monitor would not be representative of the true position of the beam. A D/S analysis could in fact indicate either zero or very large displacement. In order to avoid these problems, experience has shown that it is important to make the cavity which contains the blades relatively symmetric, and to provide a collector for the electrons. A device which we have developed for use at the NSLS beamlines X-1 and X-13 is shown in Figs. 4.4 and 4.5 [4.4]. It utilizes two pairs of TZM (tungsten-molybdenum) alloy blades which are clamped to a water cooled monolith.

Fig. 4.5 Photograph of the back side of the monitor shown in drawing.

Fig. 4.4 Cutaway drawing of the NSLS insertion device monitor.

The blades are electrically isolated from the monolith by beryllia shims which have the unique property of poor electrical conductivity but good thermal conductivity. The monolith not only serves as a heat sink for the blades but, when biased positive relative to the blades, acts as a collector for photoelectrons. This not only reduces cross-talk but also reduces the background signal due to other sources of electrons (such as ion gauges), and photoelectrons produced at other points in the beamline (such as masks and apertures).

This device has worked well at our source, and variants of it have been proposed for use at other facilities. Warwick [4.22] has proposed a similar device for use at the ALS, but has rotated the blades 45° . This tends to further reduce the effect of dipole contamination, and also keeps the maximum cross section of any blade in the beam to 1.4 times its width. This could be especially important when an insertion device is operating as a wiggler, where a horizontal blade could in principle intercept a large fraction of the insertion device output. The heat load problem is so acute at the ESRF that Herault [4.23] has proposed using four vertical blades with a very grazing incidence design (ca. 2.5°). The spacing between the pairs of blades would be optimized for best horizontal sensitivity when the insertion device is operating in undulator mode.

By rotating the blades to a more vertical orientation, both the ALS and ESRF designs trade decreased horizontal sensitivity for robust thermal properties. This is a major concern in view of the high power densities these sources can produce. The reduction in horizontal sensitivity will be most pronounced as the insertion device K increases. However, since the radiation fan is becoming wider and the power density is also decreasing, if properly accounted for in the feedback system design, this will have a minimal impact on the experiment.

It should be clear from the discussion so far that gap monitors are really best suited to feedback applications such as local orbit feedback, or optical system steering in a null current mode. Only when the blade currents are equal (zero beam displacement) is the monitor insensitive to changes in beam size σ . This implies that the monitor be mounted on a fully mobile support which can be adjusted to the desired beam position. This in turn tends to increase the monitor's cost and complexity, which can be a barrier to general application of the device. The key problem then is the sensitivity of gap-type monitors to the effective opening angle of the radiation. For reliable diagnostics we need a position monitor which is insensitive to changes in σ and the surface condition of its active elements. This leads us quite naturally to the second type of monitor we wish to discuss, the so-called area-type position monitors.

4.3 Area Monitors

The geometry of this type of detector is essentially two triangular elements nested together, similar to the electrodes of a split ion chamber [4.2], [4.11], or the diodes described by Siddons and Kraner [4.16] or Mitsuhashi, Haga, and Katsura [4.10]. Returning to our assumption of a Gaussian profile beam and referring to the

geometry illustrated in Fig. 4.6, it can be shown [4.19] that the currents on the top and bottom triangular elements can be expressed as

$$I_T = \frac{I_o(t)}{\sigma\sqrt{2\pi}} \tan\theta \int_{-h/2}^{h/2} (\delta + h/2) \exp[-z^2/2\sigma^2] dz \quad (4.8)$$

$$I_B = \frac{I_o(t)}{\sigma\sqrt{2\pi}} \tan\theta \int_{-h/2}^{h/2} (h/2 - \delta) \exp[-z^2/2\sigma^2] dz \quad (4.9)$$

where h is the height of the wafer and the pitch angle θ is defined in Fig. 4.6. If we again express displacement of the photon beam from the monitor center as δ and calculate the position as the difference over sum of the induced photo currents, we find

$$P(\delta) = \frac{I_T - I_B}{I_T + I_B} \propto 2\delta \tan\theta. \quad (4.10)$$

Note that the position signal $P(\delta)$ for the area monitor has no dependence on the photon beam size σ . In fact, for area monitors, the position signal is independent of the exact form of the photon beam profile. Also, the monitor signal is linear for the range of the entire illuminated area of the detector, which can be many millimeters.

The sensitivity of the monitor can be traded for linear range by changing the pitch angle θ of the blades (see Fig. 4.6). It is important to note, however, that care must be taken to insure that the monitor is uniformly illuminated along the axis orthogonal to the direction of measurement. If a vertical position monitor was for example underfilled in the horizontal, motion in the horizontal would be indistinguishable from vertical movement. For this reason, these monitors have so far been used at the NSLS as vertical monitors at dipole sources where these conditions are fairly easy to satisfy.

Fig. 4.6 Schematic of the illuminated section of an area monitor.

One example of a monitor of this type developed at the NSLS has been previously described, and is shown in Figs. 4.7 and 4.8 [4.4]. It has 0.3-mm-thick carbon (Grafoil) elements with a 1.2- μ gold coating which generate the photocurrent. The detector is housed in an enclosure with Grafoil windows, and a stainless steel horizontal beam defining aperture. The enclosure has been removed in Fig. 4.7 to expose the elements.

The monitor is illuminated by photons from the NSLS X-ray ring which have passed through a 5mm thick BeO disk. The purpose of this filter is two-fold, in as much as it removes 97% of the power from the beam, it reduces the heat load on the monitor which in turn enhances its thermal stability. With most of the power removed, the remaining photons are above 16 keV and therefore have a smaller opening angle than the $1/\gamma$ characteristic of the storage ring. This tends to minimize the effects of upstream apertures (such as the exit chamber slot) on the monitor. This can be an important problem for any type of monitor since it can effectively change the shape of the beam and distort the position information.

The choice of Grafoil elements for the monitor with thin gold coatings is another way of reducing the heating of the monitor. The Grafoil is essentially transparent to the photon beam it sees, and the gold thickness is calculated to provide an adequate photocurrent while absorbing as little power as possible. For the device described here, the radiated power to the monitor port is over 70 watts at 2.5 GeV and 250 ma stored beam, and the BeO filters most of that power, with about 1 watt deposited in the monitor and roughly 2 watts passing through it to the beam stop.

At the NSLS, area monitors are only used for diagnostic purposes, although they could in principle be detectors for orbit feedback and stabilization systems. If measurements of source angle and position are required, multiple (at least two) monitors are required since, except in special cases, the monitor measures only the position of the beam striking the device. By using two monitors at different distances from the machine it is a simple matter to determine these source parameters.

While the present discussion is somewhat limited in scope, it is hoped that the reader is left with the understanding that photoelectric effect monitors, when properly designed and applied, can provide a reliable way to determine photon beam position.

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Fig. 4.8 Photograph of the device with its cover removed.

Fig. 4.7 Schematic of the placement of the area monitor described in the text with respect to the machine.

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5 RECEIVERS FOR PROCESSING ELECTRON BEAM PICK-UP ELECTRODE SIGNALS

5.1 Introduction

There are several methods of determining the transverse position of the electron beam, based upon sensing either the electric field, the magnetic field, or both. An excellent overall discussion has recently been given by Robert Shafer [5.1]. At the NSLS our transverse beam position monitors each consist of a set of four circular electrodes arranged as in Fig. 5.1. There are 48 sets of pick-up electrodes in the X-ray ring and 24 in the VUV storage ring for determining the electron orbit, and a few extra sets installed for specialized purposes. When the beam passes between the four electrodes, charge is induced on each electrode, the amount depending upon the distance of the beam from that electrode. If V_a, V_b, V_c and V_d are the voltages induced on each of the four electrodes, the position of the beam is given by a difference between pairs of electrodes normalized for variations in beam current by dividing by the sum of electrode voltages:

$$x = K_x(x,y) \frac{(V_a + V_c) - (V_b + V_d)}{V_a + V_b + V_c + V_d} = K_x \frac{\Delta V_x}{\Sigma} \quad (5.1)$$

$$y = K_y(x,y) \frac{(V_a + V_b) - (V_c + V_d)}{V_a + V_b + V_c + V_d} = K_y \frac{\Delta V_y}{\Sigma} \quad (5.2)$$

Fig. 5.1
Cross section of vacuum chamber
of VUV and X-ray storage rings
showing beam position pickup electrodes.

Here, x and y are the coordinates of the beam with respect to the midpoint between these electrodes, and $K_x(x,y)$ and $K_y(x,y)$ are geometric factors which are almost constants within a distance of a centimeter from this point. It is necessary to measure the resulting voltages and process these resulting signals according to the above equations.

The method of processing these signals depends upon their time structure. The electrons circulating around the vacuum chamber are concentrated in short bunches within stability buckets produced by the accelerating voltage in the RF cavities. The charges induced on the pickup electrodes then are narrow pulses, a fraction of a nanosecond long, and would result in monopolar voltage pulses if it were not for the impedance of the cable connecting the electrode to the processing apparatus, Fig. 5.2. The capacitance between each electrode and the chamber wall is only a few picofarads and is effectively in parallel with the cable impedance (50 ohms). Thus an appreciable amount of the charge flows off the electrode while the bunch is between the electrodes, resulting in potential of opposite sign as the bunch is leaving the vicinity of the electrode. The resulting signal consists of a series of bipolar pulses, each of less than one nanosecond duration.

Fig. 5.2 Equivalent circuit of electrode and bipolar pulse.

5.2 Time Domain

One method [5.2] of signal processing that has been used in storage rings is to make these bipolar pulses wider by attenuating their higher Fourier components, usually by lengths of cables in which losses increase with frequency. The resultant pulses are sampled with a fast sample and hold device. This method depends upon short sampling apertures and careful timing which must be adjusted for each set of electrodes. The four electrodes could be sampled simultaneously with four identical devices or one device which is switched from one electrode to another. Because four devices with identical operation over a wide range of beam currents are difficult to obtain, the second option is usually used. It is often necessary to sample and average

over many beam pulses to obtain sufficient accuracy. Despite these disadvantages, this method might be used to look at and follow a particular bunch in the ring by employing suitable timing pulses to the sampler. Also it may be possible to measure a particular turn after injection with reduced accuracy.

5.3 Frequency Domain

A second approach to the signal processing is to work in the frequency domain. Because the signals are comprised of a periodic sequence of pulses induced as the bunches of electrons repetitively pass each set of electrodes, the resultant signals can be represented as a Fourier series of sinusoidal terms, which are harmonics of the orbiting frequency of the bunches. Each of the bunches generates these harmonics but the phase relationship of the contribution from each bunch will depend upon which harmonic is chosen and which buckets are filled. It can be shown that for any electrode the phase relationships between contributions from various bunches are multiples of 2π if that harmonic is an integral multiple of the RF accelerating frequency. It is usually the case that at the harmonic corresponding to the accelerating frequency, the amplitude is low due to the short bipolar nature of the pulse and so a harmonic at 3 or 4 times the accelerating frequency is chosen. Attenuation in transmission line cables rises rapidly with frequency. This is a reason for not choosing too high a harmonic. The task, when working in the frequency domain, consists of processing "sinusoidal" RF signals. The ability of following specific bunches and measuring the first turn is lost.

A straightforward method (Fig. 5.3) of processing RF signals would be to isolate the desired harmonic (a multiple of the RF frequency) from each electrode by means of a band-pass filter and amplify and rectify each signal by a separate

Fig. 5.3 Schematic representation of a system employing "identical" amplifier, detector chains with wide dynamic range.

amplifier and detector. The resultant rectified signals could be combined by means of operational amplifiers to form the required difference signals and sum signal. An analog divider is required to divide each difference by the sum. Some or all of these operations could be performed digitally by means of A/D converters with somewhat increased complication. The principal difficulties are:

1. The RF filter, amplifier and rectifier or detector for each of the electrodes must have nearly identical response over a wide dynamic range.
2. The analog divider is difficult to adjust.
3. Digital methods, if employed, require D/A converters which must be carefully matched.

An important method [5.3] avoiding use of the dividing circuits has been employed with a different type of electrode. These electrodes are cylinders split diagonally (Fig. 5.4). One is split horizontally to detect the vertical displacement and one split vertically for the horizontal displacement. The horizontal measurement is independent of the vertical measurement.

The two signals V_α and V_β from a split cylinder are filtered to extract the chosen Fourier component and amplified. One of the two signals is shifted in phase by 90° and added and subtracted from the other by means of hybrid devices. The amplitudes of the resultant signals are made equal by means of limiter devices and then combined again in a phase detector. The output is a signal proportional to $\cos(2 \arctan \alpha/\beta) \approx (\alpha-\beta)/(\alpha+\beta)$.

In this device filters, amplifiers and limiters must be accurately matched. To implement this method for our set of four electrodes, two such devices would be required. We would have to combine the signals from four electrodes to simulate the signals from two split cylinders. This might be done by signal splitters and combiners as shown in Fig. 5.4. The matching of these devices would be an additional difficulty.

5.4 NSLS Processor [5.4]

The cross section of the vacuum chamber used in both the VUV and X-ray storage rings at the NSLS was shown in Fig. 5.1 with a set of 4 circular electrodes used for electron beam position measurement. The requirements for the processing circuits are:

1. Detector sensitivity, reproducibility and noise level must allow changes in electron beam position smaller than 20 microns to be measured, and the beam must be able to be reset to this precision.
2. The device should be simple to construct and maintain using readily available components.
3. Each set of electrodes should have its own processor capable of operating independently of other devices.
4. The detector must operate over a large dynamic range of ring current, but adjustment of the device should be simple and dividing circuits eliminated if possible.

We have met these requirements by selecting one Fourier component of the button electrode signals and "time sharing" a single amplifier and detector among the

Fig. 5.4 System employing amplitude to phase conversion for use with split cylinder electrodes and a possible method of using two such systems for the NSLS electrodes.

4 electrodes. The amplifier gain is controlled by means of an automatic gain control such that the final sum signal ($V_a + V_b + V_c + V_d = \Sigma$) is compared with a reference voltage and is held to a fixed value. Under these conditions the detector and following devices are required to operate over a limited and most linear part of their dynamic range. This servo system provides the normalization for variations in beam current and eliminates the need for a conventional divider circuit.

A block diagram for the NSLS RF receiver is shown in Fig. 5.5. The coaxial cables connected to the electrodes must be identical and carefully terminated at the frequency of the harmonic chosen to avoid reflections. Also, to avoid removing all the cables when the chamber is baked out, cables employing PTFE as a dielectric are used. These cables can be degraded by radiation and must be considered as a replaceable item.

The peak amplitude of the very short signals induced on the electrodes is very much higher than that of the chosen Fourier component, in our case the third harmonic of the RF frequency (≈ 160 MHz), and may reach several hundred volts. To protect the following components from these spikes the higher harmonics are reduced by means of standard "off-the-shelf" low pass filters. Tests have shown that these filters are nearly identical in their electrical properties at our chosen frequency.

The most critical component is the single-pole four-position commutating switch. Each position must have nearly identical insertion loss, fast closing and opening times and high isolation when in the open position. We have chosen to operate the switch continuously, switching every $6 \mu\text{sec}$ to "read" all four electrodes every $24 \mu\text{sec}$. Gallium arsenide switches are used to meet these requirements. They consist of FET transistors in series-shunt configurations. These units reach 90% of their final insertion loss in a small fraction of a microsecond although the remaining 10% can take considerably longer. They are available as SPST and SP4T units. At present we use the latter type.

After the GaAs switch only a single filter is used to select the chosen harmonic, a conventional four-pole helical filter tuned to the third RF harmonic with a bandwidth of about 1%. Because of the $6\text{-}\mu\text{sec}$ sample between switching operations, there is an effective increase of the pulse width due to the transient behavior of the filter. Much of this is eliminated by adjusting closing times of the second switch located after the detector.

The RF and detector section of the device is a conventional superheterodyne type of receiver, consisting of an inexpensive commercial double balanced mixer fed by a local oscillator to produce an output of 10.7 MHz. The amplifier circuit [5.5] is an inexpensive integrated circuit made for service as an intermediate frequency amplifier for television receivers and equipped with an automatic gain control input. The output is coupled to a detector circuit, also an integrated circuit designed for television receivers. It features additional amplification besides a synchronous detector. The output of this detector is a rectified signal corresponding to signals in sequence from each of the four electrodes.

The signals are separated into four channels by means of a second SP4T switch operating in synchronism with the first switch. The conduction time for each switch position is reduced slightly to remove transient effects from the preceding

Fig. 5.5 Block diagram of NSLS beam position monitor with "time shared" amplifier and detector using automatic gain control to maintain constant sum signal.

filter, amplifier and detector. This switch is a silicon integrated circuit employing FET transistors and is designed for video switching.

Each of the four channels incorporates a resistor-capacitor smoothing circuit and a FET operational amplifier, a type chosen for low input offsets and high input impedance. Feedback is applied to each amplifier to provide a very stable gain of unity.

The difference signals $\Delta V_x = (V_a + V_c) - (V_b + V_d)$ and $\Delta V_y = (V_a + V_b) - (V_c + V_d)$ as well as the normalizing or sum signal $\Sigma = V_a + V_b + V_c + V_d$ are formed by combining these signals with operational amplifiers (Fig. 5.6). The gains of these amplifiers are also well stabilized with feedback.

Fig. 5.6 Method of combining signals with operational amplifiers
(all resistors identical)

The output of the Σ channel is compared against a reference source using another operational amplifier, the output of which supplies a signal to the gain control input of the amplifier preceding the detector. This servo system maintains the Σ output constant at a predetermined value, thus avoiding the division operation. As an added advantage all components following the amplifier operate over a relatively small dynamic range since the variation in strength of signals due to variations in beam currents has been removed.

The signals ΔV_x and ΔV_y then pass through 4 poles of low pass filtering with active filters, also constructed with operational amplifiers, fed back to give very stable gain. These filters limit the overall bandwidth of the device and reduce the higher frequency noise. The frequency determining components of these filters are mounted on plug-in modules so that they may be easily changed. Under normal conditions the cut-off frequency of these filters is set at 2 KHz, which is sufficiently high to easily make manual orbit corrections and to operate in the automatic "on-line" closed-orbit corrector system, whose speed is limited by eddy current effects in the thick aluminum vacuum chambers.

The devices are being built for all the sets of pick-up electrodes in both rings. Currently they are reproducible and sensitive to transverse position changes of less than 20 microns over a range of beam current of better than 30 to 1 and with diminished accuracy over wider ranges. Studies are underway to extend this range. The low current limit is set by electronic noise and the high current end by a gradual loss of linearity.

The noise is an increasing function of the cut-off frequency of the filters. Bench tests with simulated signals have shown that if this frequency is reduced to about 300 Hz, then the RMS noise is reduced to a value corresponding to about 5 microns of beam motion. Other experiments using the actual signal from one of our pick-up electrodes and a four way splitter have confirmed this value. This bandwidth still exceeds the response of our aluminum vacuum chambers.

To extend the upper end of the current range, the gain compression characteristics of each component in the system are being investigated in relation to the signal levels at which it must operate.

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6 REAL TIME GLOBAL ORBIT FEEDBACK SYSTEM

6.1 Introduction

Stability of the electron orbit is essential for the utilization of a low emittance storage ring as a high brightness radiation source. For an individual user, the required orbit stability can be achieved by a local bump feedback system (see Section 7). However, to install local bump feedback systems for every beamline is both costly and impractical. The coupling between different local bumps may introduce instability, and there may not be enough space for the large number of trim coils required. Here we discuss an approach for improving the stability of the closed orbit, by implementing a feedback system based upon harmonic analysis of the orbit movements and the correction magnetic fields. This harmonic feedback system [6.1, 6.2] corrects the Fourier components of the orbit nearest to the betatron tune, an approach which yields an orbit whose stability is sufficient for most experiments. The needs of the experiments requiring the tightest orbit tolerances can still be dealt with by additional local orbit feedback systems.

Harmonic orbit correction is an effective technique for eliminating global orbit distortion in storage rings resulting from inevitable magnetic field errors distributed around the ring. To our knowledge, this approach has not previously been applied dynamically to eliminate orbit fluctuations arising from time varying magnetic field errors. We have developed a harmonic feedback system which is implemented on a real time basis using relatively simple electronics. The Fourier analysis is done by a simple linear analog network. The input voltages are proportional to the orbit displacements at the detectors, and in real time the output voltages are proportional to the desired Fourier harmonic coefficients. The feedback does not force the displacement to be zero at the detectors, but forces the coefficients of a few harmonics nearest the betatron tune to vanish.

6.2 Harmonic Analysis of the Orbit

Among the different spatial Fourier components of the perturbed closed orbit the ones with frequency closest to the betatron tune ν are likely to have the largest amplitudes. If we assume that orbit errors are dominantly composed of these principal harmonics, we can use a limited number of detectors to determine their Fourier coefficients, and use a limited number of correctors to cancel them. A perturbation in a storage ring with an angular kick θ at location s_0 is described by the equation:

$$\frac{d^2y}{ds^2} + K(s)y = \theta\delta(s-s_0) \quad (6.1)$$

whose periodic solution is [6.3]

$$y = \frac{\sqrt{\beta\beta_0}\theta}{2 \sin \pi v} \cos(\pi v - |\psi - \psi_0|), \quad (6.2)$$

here β , ψ , β_0 , ψ_0 are the beta functions and betatron phases for the observation and source points respectively. Eq. (6.1) becomes that of a harmonic oscillator when we introduce the Courant-Snyder variables:

$$\phi = \frac{\psi}{v} = \frac{1}{v} \int_0^s \frac{ds}{\beta(s)}, \quad (6.3)$$

$$\eta = y/\sqrt{\beta}, \quad (6.4)$$

$$\frac{d^2\eta}{d\phi^2} + v^2\eta = v\sqrt{\beta_0}\theta\delta(\phi - \phi_0). \quad (6.5)$$

The periodic solution of this equation is

$$\eta = t \cos v(\pi - |\phi - \phi_0|) \quad (6.6)$$

with

$$t = \frac{\sqrt{\beta_0}\theta}{2 \sin \pi v}. \quad (6.7)$$

Fourier analyzing Eq. (6.6) yields

$$\eta = t \sum_{n=0}^{\infty} c_n \cos n(\phi - \phi_0), \quad (6.8)$$

$$c_0 = \frac{1}{2\pi} \int_{-\pi}^{\pi} \cos v\phi \, d\phi = \frac{1}{v} \frac{\sin \pi v}{\pi}, \quad (6.9)$$

$$c_n = \frac{(-1)^n}{\pi} \int_{-\pi}^{\pi} \cos n\phi \cos v\phi \, d\phi = \frac{2v}{v^2 - n^2} \frac{\sin \pi v}{\pi} \quad (n=1,2,3,\dots). \quad (6.10)$$

Because of the factor c_n , the harmonic component with n closest to ν is much larger than the others. For example, in the VUV ring for the vertical plane, $\nu = 1.20$, and we have:

$$\frac{c_1}{c_2} = \frac{\nu^2 - 4}{\nu^2 - 1} \approx -6, \quad \frac{c_1}{c_0} = \frac{2\nu^2}{\nu^2 - 1} \approx 6.$$

The actual fluctuations of the orbit are linear superpositions of many random kicks around the ring, and the Fourier coefficients are determined by a corresponding superposition. Discounting unlikely combinations of errors, the harmonic nearest to the tune should be much larger than others, hence we can use a very limited number of detectors properly located to obtain information about the main harmonic components. Expanding in terms of sine and cosine, we obtain

$$\eta = a_0 + \sum_{n=1}^{\infty} (a_n \cos n\phi + b_n \sin n\phi). \quad (6.11)$$

In general, the process of obtaining these coefficients is accomplished by using a Fourier transform. However, the fact that only a few components dominate makes it possible to accurately estimate these few harmonic coefficients by solving a small number of linear equations. We shall keep only the terms nearest the main harmonic components in the Fourier series.

6.3 The VUV-Ring System

The harmonic global orbit correction uses the fact that the orbit distortion is dominated by its harmonic components nearest to the tune. To carry out an harmonic orbit correction, we first measure the orbit, then Fourier analyze its displacements. To implement real time harmonic feedback, the problem is how to use a limited number of detectors and trims to realize this process. We have developed a scheme to accomplish this task [6.1,6.2].

The NSLS VUV ring has a vertical tune of 1.2, and the first harmonic component dominates. We can approximately write

$$\eta = a \cos \phi + b \sin \phi. \quad (6.12)$$

There are only two unknown Fourier coefficients a and b , and in principle only the displacements at two locations need to be determined to calculate a and b . When we have 4 detectors, we can use a least square method to calculate a and b . When there are only two detectors, they must be separated by nearly $\pi/2$ phase advance to maximize the determinant of the equations, so they cannot be distributed uniformly. When there are 4 detectors we can distribute them uniformly around the ring so the orbit improvement is more uniform around the ring. The redundancy of detectors

also improves the accuracy, because the correlation between the signals from different detectors enhances the signal to noise ratio.

The least squares problem is to determine a and b to minimize the sum:

$$S = \sum_{i=1}^4 [\eta_i - a \cos \phi_i - b \sin \phi_i]^2. \quad (6.13)$$

Here η_i is the orbit displacement signal divided by $\sqrt{\beta_i}$ at detector i. Differentiation of S with respect to a and b gives in terms of matrix notation,

$$\begin{pmatrix} a \\ b \end{pmatrix} = F \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \end{pmatrix}. \quad (6.14)$$

Here F is a matrix which is completely determined by the phases ϕ_i of the detectors. It is noted that these phases are known quite accurately, particularly when the ring has a 4-fold symmetry (4 superperiods), as is the case for the VUV ring. If the 4 detectors are periodically distributed around the ring, the phase advance of two detectors next to each other is exactly $\pi/2$. Clearly, the matrix operation (6.14) can be carried out by a simple linear analog circuit F.

In a similar way, the trim strengths required to generate an orbit with Fourier coefficients -a and -b can be calculated by a matrix multiplication:

$$\begin{pmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \end{pmatrix} = T \begin{pmatrix} -a \\ -b \end{pmatrix}. \quad (6.15)$$

This matrix operation can be carried out by another simple linear analog circuit T.

Based upon these two networks we have built the feedback system, which is illustrated in Fig. 6.1. It provides for the correction of the sine and cosine components of the first harmonic of the vertical orbit distortion. The output of the 4 PUE's is the input of the Fourier analysis 2 by 4 matrix network F. As described above, the output of F is the two voltages corresponding to the two Fourier coefficients of $\sin \phi$ and $\cos \phi$ for the vertical feedback with tune 1.20. The linear network with 4 by 2 matrix T is used to generate different trim current combinations.

The networks F and T are determined theoretically in terms of the Courant-Snyder phases at the detectors and trims. In order that the actual system have two independent channels, we introduce the empirically determined matrix M to diagonalize the system, so the transfer matrix from the input of the M block to the output of the F block is unity, thus providing two independent channels (cosine and sine) for

Fig. 6.1 Global Feedback System for VUV-Ring.

feedback. We use the two boxes g_1 , g_2 in Fig. 6.1 to represent the servo circuits for the two channels. Once the loop is closed, we realize the harmonic feedback in real time. The detailed description of the function of M is given elsewhere [6.1,6.2]. We have found that the network M can be determined very accurately by carrying out simple measurements on the storage ring as the feedback system is being installed. The matrix M corresponds to a fine adjustment of the system.

An experiment based on this scheme has been carried out on the VUV ring [6.2]. The 4 PUE RF detectors utilized are uniformly distributed about the ring with their phases separated by $\pi/2$. The 4 trims used are also symmetrically distributed about the ring with $\pi/2$ phase separation. The results of the experiment show that the maximum orbit fluctuation around the ring is reduced by a factor between 3 and 4, in agreement with the prediction of a numerical simulation. To check the global improvement, the signal power spectrum was measured at 18 PUE locations, with the feedback loop open and closed. When the NSLS booster is ramping, it induces an orbit deviation at its repetition rate of 0.67 Hz. All around the VUV ring this movement is observed, and the power spectrum exhibits peaks at 0.67 Hz and its harmonics. We plot in Fig. 6.2 the amplitude of the second harmonic observed at 18 PUE's, comparing the amplitudes with the loop open and closed. The global improvement is clearly demonstrated. For first experiments, the feedback bandwidth was not optimized. This can be significantly improved in future work.

Fig. 6.2 Global improvement of orbit stability in VUV ring upon closing feedback loop.

6.4 The X-Ray Ring System

Recently, based on experience with the VUV ring global orbit feedback system, we have developed an X-ray ring vertical orbit feedback system. The X-ray ring has 8 superperiods, with a vertical betatron tune of 6.2. We have selected 8 PUE's and 16 trims, symmetrically distributed around the ring, with one PUE and 2 trims per superperiod. The system is designed to eliminate 3 harmonic components of the orbit distortion utilizing 6 Fourier coefficient channels, corresponding to $\cos 5\phi$, $\cos 6\phi$, $\cos 7\phi$, $\sin 5\phi$, $\sin 6\phi$, $\sin 7\phi$, respectively. Thus we generalize the matrix F in Eq. (6.14) to a 6 by 8 matrix, and the matrix T in Eq. (6.15) to a 16 by 6 matrix. Simulation shows that the system should reduce the maximum displacement by a factor 5, and the rms displacement by a factor 6, for the worst noise source location.

The F matrix circuit for the VUV ring feedback system consists of many potentiometers, each corresponding to one matrix element. Since the X-ray ring system has much larger F and T matrices, we decided to use MDAC (multiplying digital to analog converters) instead of the potentiometers. The output signal of an MDAC is equal to the input multiplied by a ratio determined by a digital input from a computer. Hence we can think of this MDAC as a digitally controlled potentiometer. Both the F and T matrices are made of a number of MDAC boards, each with 16 MDAC's. The MDAC boards are designed to be modular, so that they can be assembled in many different ways to form either F or T matrices, with different numbers of input and output channels. For example, the F matrix circuit is a crate, which consists of 6 MDAC boards. The 8 PUE receiver output signals are wired to

all of the 6 boards, providing the 8 inputs for each board. Each board corresponds to one of the 6 Fourier coefficient channels. Thus the MDAC boards can be mass produced, and used for not only the X-ray ring vertical orbit feedback system but also for the X-ray ring horizontal orbit feedback system and upgraded VUV ring systems.

Since with MDAC boards it is very easy to set up the matrix elements by simply loading the F and T matrix files into the computer, the M matrix mentioned in Section 6.3 and shown in Fig. 6.1, and used for diagonalization purpose for the VUV ring system, is now combined with the T matrix. Initially, the F and T matrices are calculated by theory, and loaded into the F and T crates. Then the 6 by 6 response matrix R, from the input of the T matrix to the output of the F matrix, is measured experimentally. Next, the old T matrix is multiplied by the inverse matrix of R to generate a new T matrix, and the result is loaded into the T crate. The process can be iterated until the new response matrix, measured after the new T matrix is loaded, is sufficiently close to a unit matrix. Actually, after only one iteration, the off-diagonal elements of the R matrix became 40 dB smaller than the diagonal elements, providing 6 independent channels, each controlling one Fourier coefficient of the orbit distortion.

To check the accuracy of the F matrix, we drove one trim magnet by a sinusoidal signal (about 1 Hz), and measured the relative weights of the 6 outputs of the F matrix, then compared the results with the theoretical F matrix output and the Fourier coefficients calculated from Eq. (6.10). The agreement between the measurement and the theoretical F matrix output (normalized so that the maximum component is one), is about 3% with maximum deviation of 6% for 16 different sets of measurements. This good agreement indicated that the prediction from computer simulation of an improvement factor of 5 to 6 could be realized.

When we closed the servo feedback loops for all 6 Fourier coefficient channels, we obtained significant improvement of the orbit stability. Figure 6.3 shows the improvement observed on the X1 beam line photo-emission detector position signal, comparing open and closed loops. Figure 6.4 shows both the long-term and short-term beam position movement at PUE31 when we turned the global feedback loops on and off every 30 minutes during an 8 hour machine study period. We took 16 different measurements such as the one shown in Fig. 6.4, measured the maximum excursions (peak to peak) for both open and closed loops, and plotted the results in Fig. 6.5 as the maximum excursion vs. the PUE number, providing a clear picture of the global improvement.

We shall now discuss how to operate the global orbit feedback system and several local orbit feedback systems simultaneously. Several local feedback systems have been installed in the X-ray ring following Hettel's work [6.4]. Based on the local bump feedback system concept, the author further developed a simple method to stabilize both angle and position signals for a beam line (Section 4.2 of Ref. [6.5]). The local feedback system has four trim magnets and two position detectors, P_1 and P_2 . Hettel developed a method to obtain an accurate strength ratio between the 3 magnets of a trim triplet, forming a local bump that only steers the electron beam inside the bump [6.4]. We use two sets of trim triplets consisting of t_1, t_2, t_3 and t_2, t_3, t_4 , to form two independent local bumps. The response matrix R from the two

Fig. 6.3 Improvement observed on the X1 beamline photoemission detector.

Fig. 6.4 Long-term and short-term beam position movement at PUE31 when global feedback was turned on and off every 30 min during an 8-hr machine study period.

input terminals of these two local bumps to the output of the two detectors is a 2 by 2 matrix with non-zero off-diagonal elements, i.e., each of these two local bumps can influence the output of both detectors. To obtain two independent feedback channels, we again use a matrix M as we did for the global feedback system, which is the inverse matrix of the response matrix R . It is easy to see that the response matrix

Fig. 6.5 Global improvement of orbit stability in X-ray ring upon closing feedback loop.

from the input of the M matrix to the output of the two detectors is a unit matrix, forming two independent feedback channels. Closing the feedback loops on these two channels stabilizes the signals of both detectors, thus stabilizing both the angle and the position of the photon beam. Since both loops control local bumps, the system generates only local feedback.

It happens that two of the PUE's (P_{g1} , P_{g2}) used for the global feedback system are located inside the local feedback system. As shown in Fig. 6.6, they are near the two trims t_1 , t_4 , thus producing a small coupling between the global and local feedback systems. We consider the whole storage ring with the global feedback system loop closed and the two local bumps with the two local feedback loops open

Fig. 6.6 Local feedback system for X-ray ring insertion utilizing four trim dipole magnets t_1 , t_2 , t_3 , t_4 and two PUE's P_1 and P_2 .

Two PUE's (P_{g1} , P_{g2}) used for the global feedback system are located inside the local bump.

as a new system with the two inputs of the M matrix as input terminals, and the two outputs of the two detectors P_1 , P_2 as output terminals. Since the servo loops of the global feedback system are designed to be stable with proper frequency compensation, this new system is stable. However, the response matrix of this new system is no longer a unit matrix, because the global feedback system responds to the driving signals in the local feedback loop through the signals from the two PUE's (P_{g1} , P_{g2}), and changes the output of P_1 , P_2 . We remeasured the response matrix R , and found that the off-diagonal elements are 20% of the diagonal elements. Using the inverse matrix of this new response matrix R to multiply the matrix M , and dialing the result into the M box, we reestablished the system with the unit response matrix, i.e., with two independent channels, as we did before. After redesigning and closing the servo loops, we managed to successfully close both the global and the local feedback loops.

In Fig. 6.7, we show the results of this combined global-local system. The top part of the diagram is the signal from one of the PUE RF receivers in the local feedback system. The lower part is the correction signal in one of the local feedback loops. When both global and local loops are open, the correction signal is zero, and the beam movement amplitude is about $10\ \mu\text{m}$, introduced by a booster signal of frequency 0.67 Hz. When only the global feedback loops are closed, the beam movement is reduced to about $2.5\ \mu\text{m}$. When only the local feedback loop is closed, the beam motion is reduced to $2\ \mu\text{m}$, but the correction signal is large. However, when both the global and the local feedback systems are closed, the beam motion is further reduced to about $1\ \mu\text{m}$, and the correction signal is reduced by a factor 5. This result shows that the global feedback system can greatly reduce the trim dipole strengths of the local feedback systems. This is particularly useful when the orbit excursion is very large and pushes the local feedback system to near saturation, as happens sometimes for the horizontal orbit local feedback systems in the X-ray ring.

The new X-ray ring vertical global orbit feedback system has been in operation since the beginning of February 1991. It significantly increases the orbit stability greatly improving the quality of the photon beams. One example is shown in Fig. 6.8, where we plot the X-ray intensity fluctuations observed from a sample in the AT&T beam line X16A, measured during three different periods (Nov. 90, Jan. 91, and Feb. 91). Note the very large reduction of the fluctuation after the global orbit feedback system went into operation in Feb. 91.

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Fig. 6.7 Results for combined global-local system.

Fig. 6.8 Intensity fluctuations observed from sample in beamline X16A.

7 LOCAL ORBIT FEEDBACK

7.1 Introduction

Critically aligned experiments are sensitive to small changes in the electron beam orbit. At the NSLS storage rings, the electron beam and photon beam motions have been monitored [7.1, 7.2] over the past several years. In the survey conducted in 1986 by the NSLS Users Executive Committee, experimenters requested the vertical beam position variation and the vertical angle variation, within a given fill, remain within $10\ \mu\text{m}$ and $10\ \mu\text{r}$, respectively. This requires improvement in the beam stability by about one order of magnitude.

At the NSLS and SSRL [7.3] storage rings, the beam that is originally centered on the position monitor by a dc orbit correction is observed to have two kinds of motion: a "dc" drift over a storage period of several hours and a beam "bounce" about its nominal position. These motions are a result of the equilibrium orbit not being held perfectly stable due to time-varying errors introduced into the magnetic guide field by power supplies, mechanical vibration of the magnets, cooling water temperature variations, etc.

Our approach to orbit stabilization includes (1) identifying and suppressing as many noise sources on the machine as possible, (2) correcting the beam position globally (see Section 6) by controlling a number of correctors around the circumference of the machine, and (3) correcting the beam position and angle at a given source location by position feedback using local detectors and local orbit bumps. The third approach, called "Local Orbit Feedback" will be discussed in this section.

7.2 Three-Magnet Bump

A local orbit bump is a deflection of the electron beam over a limited portion of the ring azimuth. A local bump deflecting the electron beam at source point s by a distance d can be made by using trim magnets with angular deflections of δ_1, δ_2 , and δ_3 at locations 1, 2 and 3 respectively (see Fig. 7.1). The strengths of these kicks are chosen to make the deflection local, i.e., to assure that the reference orbit has no disturbance outside the azimuthal segment between points 1 and 3.

Fig. 7.1 Three-Magnet Bump

The magnitudes of the kicks δ_1, δ_2 , and δ_3 are co-related by a single quantity, say δ , and this co-relation can be predicted from the beta function and phase advance. Electron beam position y_{sn} and angular displacement y'_{sn} at point s due to a kick δ_n at point n are given by the following expression, using the lattice parameters of the ring [7.4]:

$$y_{sn} = \delta_n \frac{\sqrt{\beta_n \beta_s}}{2 \sin \pi \nu} \cos(\pi \nu - |\Phi_s - \Phi_n|) , \quad (7.1a)$$

$$y'_{sn} = \frac{\delta_n}{2 \sin \pi \nu} \sqrt{\frac{\beta_n}{\beta_s}} [\pm \sin(\pi \nu - |\Phi_s - \Phi_n|) - \alpha_s \cos(\pi \nu - |\Phi_s - \Phi_n|)] \quad (7.1b)$$

where the $+$ sign is used if $\Phi_s > \Phi_n$. For a three-magnet bump to be local, the sum of deflections and angular deviations at point 3 due to kicks at 1, 2, and 3 should be zero, which is represented as follows:

$$y_{31} + y_{32} + y_{33} = 0 , \quad (7.2a)$$

$$y'_{31} + y'_{32} + y'_{33} = 0 , \quad (7.2b)$$

where y_{31}, y_{32} etc. are defined by Eqs. (7.1a) and (7.1b). These equations may be rewritten as

$$A_{31} \delta_1 + A_{32} \delta_2 + A_{33} \delta_3 = 0 , \quad (7.3a)$$

$$B_{31} \delta_1 + B_{32} \delta_2 + B_{33} \delta_3 = 0 . \quad (7.3b)$$

The coefficients A_{ij}, B_{ij} in Eqs. (7.3a) and (7.3b) are determined from Eqs. (7.1a) and (7.1b), using local values of the beta function and phase advance. Equations (7.3a) and (7.3b) may be solved for δ_2 and δ_3 in terms δ_1 , yielding

$$\frac{\delta_2}{\delta_1} = -\sqrt{\frac{\beta_1}{\beta_2}} \cdot \frac{\sin(\Phi_3 - \Phi_1)}{\sin(\Phi_3 - \Phi_2)}, \quad (7.4a)$$

$$\frac{\delta_3}{\delta_1} = \sqrt{\frac{\beta_1}{\beta_3}} \cdot \frac{\sin(\Phi_2 - \Phi_1)}{\sin(\Phi_3 - \Phi_2)}. \quad (7.4b)$$

For the local bump, we introduce the relative weights K_1 , K_2 , K_3 and specify the strength of the trim dipoles according to $\delta_1 = K_1\delta$, $\delta_2 = K_2\delta$ and $\delta_3 = K_3\delta$. Substituting values determined in Eqs. (7.4a) and (7.4b) into Eqs. (7.1a) and (7.1b), the position and angular displacements at a source point "s" within the bump may be determined in terms of a single trim strength δ_1 or δ_3 .

When s is between 1 and 2, the position and angular displacements are as follows

$$y_s = \delta_1 \sqrt{\beta_1 \beta_s} \sin(\Phi_s - \Phi_1). \quad (7.5a)$$

$$y'_s = \delta_1 \sqrt{\frac{\beta_1}{\beta_s}} [\cos(\Phi_s - \Phi_1) - \alpha_s \cdot \sin(\Phi_s - \Phi_1)]. \quad (7.5b)$$

When "s" is between 2 and 3, the position and angular displacements are as follows

$$y_s = \delta_3 \sqrt{\beta_3 \beta_s} \sin(\Phi_3 - \Phi_s), \quad (7.5c)$$

$$y'_s = -\delta_3 \sqrt{\frac{\beta_3}{\beta_s}} \cdot [\cos(\Phi_3 - \Phi_s) + \alpha_s \cdot \sin(\Phi_3 - \Phi_s)]. \quad (7.5d)$$

This property makes it sufficient to use only one detector as a part of the local feedback system. A simple block diagram of such a system is shown in Fig. 7.2. The position detector output c is subtracted from the reference signal r to provide an error signal e. This error signal output is amplified and phase compensated in the compensation amplifier which then drives the bump with relative weights given by the coefficients K_1 , K_2 and K_3 . Three power supplies (1, 2 and 3) excite three-magnet trims 1, 2 and 3.

$$y_{s_1} = -\delta_{3a} \sqrt{\frac{\beta_3}{\beta_{s_1}}} [\cos(\Phi_3 - \Phi_{s_1}) + \alpha_{s_1} \sin(\Phi_3 - \Phi_{s_1})] + \delta_{2b} \sqrt{\frac{\beta_2}{\beta_{s_1}}} [\cos(\Phi_{s_1} - \Phi_2) - \alpha_{s_1} \sin(\Phi_{s_1} - \Phi_2)] . \quad (7.6b)$$

For bump a, let the relative weight be K_{1a} , K_{2a} and K_{3a} and for bump b, let the relative weight be K_{2b} , K_{3b} and K_{4b} . Now, for two source points s_1 , and s_2 within the range of the bumps, we may write

$$\begin{bmatrix} y_{s_1} \\ y_{s_2} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \cdot \begin{bmatrix} \delta_a \\ \delta_b \end{bmatrix} = A \cdot \bar{\delta} \quad (7.7a)$$

where

$$a_{11} = K_{3a} \sqrt{\beta_3 \beta_{s_1}} \sin(\Phi_3 - \Phi_{s_1}) ,$$

$$a_{12} = K_{2b} \sqrt{\beta_2 \beta_{s_1}} \sin(\Phi_{s_1} - \Phi_2) ,$$

$$a_{21} = K_{3a} \sqrt{\beta_3 \beta_{s_2}} \sin(\Phi_3 - \Phi_{s_2}) ,$$

$$a_{22} = K_{2b} \sqrt{\beta_2 \beta_{s_2}} \sin(\Phi_{s_2} - \Phi_2) . \quad (7.7b)$$

7.4 Decoupling

In general, a three-magnet bump will displace the beam simultaneously at both detectors located at s_1 and s_2 as shown in Fig. 7.4. For example, when bump a (1, 2 and 3) displaces the beam at s_1 by d_1 , it also displaces the beam at s_2 by d_2 . This coupling is not desirable in feedback systems. Let us consider a four-magnet bump, such that beam displacements at s_1 and s_2 are d_1 and zero, respectively (as shown by dotted line in Fig. 7.4). Such a bump is called a decoupled bump and is highly desirable since it affects only one detector position. Similarly, a second four-magnet bump can be developed such that it has no effect at location s_1 , but controls the position at location s_2 . By using these two four-magnet bumps, the positions at two locations are controlled independently.

Fig. 7.4 Four-Magnet Decoupled Bump

The Eq. (7.7a) can also be represented by the diagram given in Fig. 7.5a. The correction voltages v_1 and v_2 act on the bumps δ_a and δ_b to produce two outputs y_{s1} and y_{s2} . To decouple beam motion at the two source points, we must find C, such that

$$[C] \cdot [A] = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \cdot \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} b_{11} & 0 \\ 0 & b_{22} \end{bmatrix}. \quad (7.8)$$

Letting $c_{11} = c_{22} = 1$ and solving for the remaining coefficients, we get

$$c_{12} = - \frac{a_{12}}{a_{22}}, \quad (7.9a)$$

$$c_{21} = - \frac{a_{21}}{a_{11}}. \quad (7.9b)$$

The matrix C can be inserted as shown in Fig. 7.5b, such that two outputs are decoupled. This matrix C and the bumps a and b can be combined to form new bumps a' and b' . This representation is shown in Fig. 7.5c and the new bump values are calculated by the following equations:

$$\delta'_a = \delta_a - \frac{a_{12}}{a_{11}} \cdot \delta_b. \quad (7.10a)$$

$$\delta'_b = - \frac{a_{21}}{a_{11}} \cdot \delta_a + \delta_b. \quad (7.10b)$$

Fig. 7.5 Decoupling

7.5 Detectors

The detector is a fundamental component of the feedback system and can limit its performance. The basic requirement of a detector is to generate a continuous signal proportional to the beam displacement. This signal must have the following performance criteria:

1. be accurate and stable,
2. be independent of the beam intensity over the operating range,
3. have good frequency response to represent fast beam motion accurately.

There are two categories of detectors: the electron beam pick-up electrodes (Section 5) and the photon beam position monitors (Section 4). The electron beam pick-up is placed over the electron path, normally on the beam pipe; the photon beam detector is external to the storage ring in line with the X-ray beam. The possible locations of these detectors are shown in Fig. 7.6.

Fig. 7.6 Possible Location of Detectors

As discussed in Section 5, a high precision RF receiver for the pick-up electrodes has been developed at the NSLS. This detector converts RF signals from pick-up electrodes to low frequency signals proportional to the beam displacement from the electrical center of the pick-up electrodes. The characteristics of these low frequency signals meet all above criteria.

For the photon beam, two types of detectors are being used for monitoring position: photoemission (Section 4) and split ion chamber. The signals from photon detectors are processed by sum-difference amplifiers and dividers to extract beam position. The performance of such devices is basically limited by vibration and thermal distortion of the mirror.

7.6 Trim Magnets and Power Supplies

The trim magnets should provide consistent and repeatable magnetic steering fields. At the NSLS, these magnets are constructed with two sets of coils, a vertical set and a horizontal set, and use laminated low-hysteresis steel having a window-frame cross section. These magnets are energized with commercially available wideband linear power supplies rated at ± 10 amperes [7.6].

7.7 Compensation and Servo Circuits

A simplified block diagram of the local beam steering feedback system is shown in Fig. 7.7. The frequency response of the uncompensated system, $C(\omega)/M(\omega)$ (where $C(\omega)$ is the Fourier Transform of $c(t)$, etc.) is measured by introducing a test signal into the bump input. For the NSLS storage rings, this is found to have a rather flat amplitude response up to approximately 1 kHz while the phase response rolls off quickly and crosses the 180° line at about 200 Hz. This phase shift is due to eddy currents induced in the relatively thick NSLS aluminum vacuum chamber by the time-varying magnetic field. The compensation amplifier provides the appropriate lead-lag networks and a high dc gain.

Fig. 7.7 Local Beam Steering Feedback System

The reduction of the positional noise due to the action of the feedback system may be expressed analytically by referring to the simplified Fig. 7.7. In this figure, n represents the ambient positional noise introduced by orbit fluctuations in the ring, o is the correction generated by the feedback system, c is the net motion of the beam, and r is the reference signal. The net motion is related to the ambient orbit fluctuations and the feedback correction by

$$C(\omega) = N(\omega) - O(\omega) . \quad (7.11)$$

Introducing the error signal

$$E(\omega) = R(\omega) - C(\omega) , \quad (7.12)$$

and the gain A of the feedback loop, the correction generated by the feedback is determined by

$$O(\omega) = E(\omega) A G(\omega) H(\omega), \quad (7.13)$$

where $G(\omega)$ and $H(\omega)$ are feedback system transfer functions (see Fig. 7.7). Using (7.11) to (7.13), we solve for the net motion $C(\omega)$ of the orbit with the feedback loop closed, obtaining

$$C(\omega) = \frac{N(\omega) - R(\omega) A G(\omega) H(\omega)}{1 - A G(\omega) H(\omega)} . \quad (7.14)$$

In our system we use a DC reference signal, hence $R(\omega)=0$ for $\omega \neq 0$, and the reduction in orbit fluctuations is described by

$$C(\omega) = \frac{N(\omega)}{1 - A G(\omega) H(\omega)} . \quad (7.15)$$

From the above expression it is clear that with the loop open (i.e. $A = 0$), $C(\omega) = N(\omega)$. With the loop closed, the various frequency components of the noise in the output are reduced by the available gain. The maximum loop gain is limited by consideration of the dynamic stability of the system.

7.8 NSLS Feedback System

Recently, two automatic local feedback systems, controlled by microprocessors, have been installed and commissioned in the NSLS X-ray storage ring. In each system, the position of the electron beam is stabilized at two locations by four independent servo systems, two horizontal and two vertical. A block diagram of this system is given in Fig. 7.8.

Fig. 7.8 Block Diagram of NSLS Beam Steering System for Position and Angle Control

The RF detectors are used to sense the electron beam position at two pick-up electrodes, shown on the right of Fig. 7.8. The x outputs from these detectors are used as inputs into the horizontal feedback system as shown. Similarly, the y outputs are used for the vertical feedback system (not shown in the figure).

The RF detector output is fed into the signal processor which subtracts it from the target or the reference value. The reference value is fed from the computer and can be changed as desired. The multiplying d to a converters (mdac) are used to provide a "soft" on/off control for the feedback loops. To achieve this, the microprocessor sends mdac set values in small increments to create a ramping effect. This is desirable to eliminate any transient condition which may occur if it is turned on instantly. Two servo amplifiers, one for each position, provide the "dc" gains and the required compensations.

The outputs of the mdac are combined in pairs by adding corresponding signals which then are "phase equalized" in the equalizer circuits. The output of the equalizer circuit drives the power supply via another adder. The computer provides the other input to this adder and these computer settings are used to set the equilibrium orbit before the loop is closed. The four power supplies (PS1 to PS4) excite the four trim magnets (TM1 to TM4) for each plane.

These local feedback systems have been used successfully and are fully operational on the NSLS X-ray ring. The results from X25 beamline are shown in Fig. 7.9. Two RF detectors are connected to PUE30 and PUE31 and are used for the local feedback for this beamline. The top trace in Fig. 7.9 shows the vertical beam motion in time domain with vertical feedbacks ON and OFF. From this trace, we see that the beam motion induced by the NSLS Booster (~ 0.66 Hz) is clearly reduced from this trace, when loops are turned ON. The bottom trace is the

frequency spectrum of the vertical beam motion at PUE31 with loop ON and OFF. The improvement at the second harmonic of the NSLS Booster is better than 33 db as shown by peaks y_a and y_b . The bandwidth of this system is about 30 Hz.

Fig. 7.9
Beam Motion Reduction
with Feedback ON.

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8 ACTIVE INTERLOCK SYSTEM FOR HIGH POWER INSERTION DEVICES IN THE X-RAY RING

8.1 Introduction

In modern synchrotron radiation rings photon beams generated by high power insertion devices (IDs) may be sufficiently intense to cause severe thermal damage to the machine vacuum chamber if mis-steered. Thus when operating a storage ring with the IDs, great care must be exercised to prevent mis-steering of the electron beam orbit.

At present, the X-ray ring operates with three IDs, namely two hybrid wigglers (HBW) at X-21 and X-25, and a 5-Tesla superconducting wiggler at X-17. All wigglers are located in low-beta straight sections. Power density in the X-25 HWB photon beam is of the order of 1.75 kW/mrad^2 at 250 mA stored current. The power carried by a photon beam from an insertion device varies as $i\gamma^2K^2$, where i is the beam current, γ is the energy and K is the ID field factor. In the straight sections, beam orbit may be deflected by as much as $\pm 8 \text{ mrad}$ without scraping the chamber wall. For various reasons it was not possible to design the X-ray ring vacuum chamber to be safe under all possible operating conditions, however, the chamber is safe for $i < 7 \text{ mA}$, all horizontal beam deflection angles (except in the case of the SCW) and for vertical angles $< \pm 2.5 \text{ mrad}$. Vertical deflections $> \pm 2.5 \text{ mrad}$ could expose parts of the chamber to incident radiation and must be avoided. The X-17 wiggler is not safe at low energy and high wiggler field (since the horizontal opening angle $\theta \approx K/\gamma$ becomes large enough to allow the wiggler chamber itself to be illuminated in the case of a large horizontal orbit distortion).

To protect the machine vacuum chamber from damage due to mis-steered beams, an interlock system has been developed and installed. This system utilizes active beam position detectors which continuously monitor beam motion in each of the ID straight sections and logic circuitry which interrupts the RF and dumps the stored beam in the case of a fault. The time interval within which the system must respond to an out-of-range beam position has been calculated for the worst case to be $\approx 30 \text{ msec}$. A portion of the vacuum chamber in a typical machine straight section which is protected by the interlock is shown in Fig. 8.1.

The X-ray ring active interlock system monitors the motion of the electron beam orbit in each straight section both upstream and downstream of the insertion device with active beam position monitors (BPMs). The BPMs obtain beam positional information from dedicated RF pick-up electrodes (PUEs) built into the chamber wall [8.1,8.2]. Window comparators monitor BPM outputs and generate fault signals for out of range signals. Fault signals are then transmitted to a central location to momentarily interrupt the low level drive to the accelerator RF system which "dumps" the circulating beam.

In the design of the system, various beam position sensors were considered. These included devices such as thermal and pressure sensors, radiation monitors as well as the NSLS-developed RF BPMs. After careful consideration, it was decided

Fig. 8.1 Vacuum Chamber in a Straight Section

that the BPMs would have the best response, be most reliable and would be easiest to implement.

Reliability of the system is ensured by using two completely redundant channels starting from the BPMs all the way through to the low-level RF switches with all components hard-wired (i.e. no software links). Each redundant circuit interrupts the RF drive independently. Operation of critical system components is continuously monitored in the background by dedicated microcomputers which generate warning signals to the machine operator in case of a problem. The overall system is periodically tested with beam at safe levels of beam current using one of the main NSLS control computers. Test software has been written to automatically generate local orbit "bumps" and to move the beam at each location until a trip level is reached and the RF is pulsed off. Such tests are routinely performed prior to normal machine fills. The software checks measured values against stored parameters to determine whether all criteria have been satisfied and generates a "PASS-FAIL" report at the end of the test.

8.2 System Description

A design of an interlock prototype has been described [8.3]. Present system realization differs from the prototype in several aspects such as circuit topology,

inhibit functions, testing philosophy, etc. and has also been described [8.4]. The design and basic operation of the system now operating in the machine will be described by referring to the block diagram in Fig. 8.2. In each of the straight sections containing an insertion device, vertical position of the stored beam is monitored both upstream and downstream of the device at the location of the dedicated RF PUEs. For reliability, two BPMs are connected to each PUE, one from interlock channel A and the other from channel B. The output of each BPM is monitored by a window comparator in the local logic chassis (LLC). The center of the window is set to match the offset voltage of the BPM if any, and the width of the window is adjusted for the allowable range of beam displacement at the PUE. If the comparator detects an out-of-range signal, it generates a fault bit which is transmitted to the Central Logic Chassis (CLC). After receiving a fault signal, CLC sends an interrupt request to the RF Interface Chassis (RFI), which then momentarily interrupts the low level RF drive signal to all RF systems (RF1, RF2, etc.). The RF interrupt pulse must be long enough to "dump" the beam (few milliseconds) yet short enough so as not to disturb the thermal equilibrium of the RF transmitters and accelerating cavities. The presence of beam in the machine is monitored independently by two logarithmic amplifiers and if the beam is present at the end of the interrupt interval, all RF systems are crashed by crow-barring the screen power supplies. Response time of each interlock channel has been intentionally slowed down to approximately 20 ms to avoid false trips.

Each of the local nodes, as well as the central node of the system, contains a dedicated micro-computer. The computer hardware consists of a Motorola VME-133 CPU, battery backed-up memory, GPLS board (NSLS General Purpose Interface Board), ADC and bit I/O boards--all housed in a VME-format crate. The central-node micro also services the RFI. The function of each micro is to monitor the status of latches, set control bits, perform digital filtering of BPM output signals, perform comparison tests between redundant detectors, and generate video displays. All of the dedicated micros communicate with the main NSLS control computers via Ethernet.

The following is a description of some of the more important features of the interlock system.

8.2.1 First-Event Latches

The LLCs and the CLC contain so-called first-event latches to permit the capturing of momentary window comparator fault signals. In the LLCs, the outputs of all comparators in both the A and the B interlock channels are connected to a common latch. In the CLC, the A faults and the B faults have separate latches. The first-event latches can be made "transparent" by means of control bits, which is useful in system testing.

Fig. 8.2 Block Diagram of System

8.2.2 Local and Global Inhibits

To permit testing of the individual blocks and of the overall system, local as well as global inhibit functions have been incorporated in the design. A local node may be automatically inhibited either if the gap of the insertion device is open or if

the gap field is low. Both the gap and/or the field are checked twice with redundant limit switches and current transformers or Hall probes. The entire interlock system is automatically inhibited for beam currents < 7 mA. Again, beam current is checked twice with MIL-specified solid-state RF detectors and threshold detectors. Any of the inhibit signals may be overridden with control bits from the micro-computer to force-activate the interlock. A scheme is available to lock the state of the inhibit override bits.

8.2.3 Fault Interrupt

Fault signals generated by comparators in the LLCs generate an interrupt to the local micro. The interrupt causes the last digitized output from each BPM prior to beam dump to be saved in memory.

8.2.4 Automatic Testing

With micro-computers interfaced to the interlock, it is possible not only to monitor individual status bits and/or analog readbacks or set control bits, but also to perform a whole range of automatic system tests. For example, using the global inhibit feature, operation of each leg of the interlock can be tested automatically at low beam current without dumping the beam. Beam may be dumped using the beam dump command, which is introduced into the circuit ahead of the inhibit signal input. Central micro, which generates beam dump signals and monitors the output of the log amp detectors, can measure the propagation delay through the RFI and the high level RF system. Thus, in general various parts of the interlock may be checked separately and, with an overlap between these parts, integrity of the overall system can be guaranteed.

As mentioned earlier, the local micros continuously monitor the outputs of the BPMs. After digitizing and filtering, signals from redundant detectors are compared with each other. Similarly, the central micro compares the outputs of two RF log-amp detectors monitoring beam current signal from a stripline monitor and compares them with the ring beam current transformer output. To ensure that all micros are alive and performing the background comparison tests, "heartbeat" signals from the micros are monitored by the LLCs and the CLC.

8.2.5 Status Display

The state of the interlock, status of the latches, inhibits and background faults are displayed on a display panel in the control room which is directly connected to the CLC. In addition to display lights, the panel contains two manual lock-switches and a sonic alarm. One of the switches resets all latches (global reset) and the other dumps the beam. In addition to the display panel, a video monitor is used to display the overall status of the system including the RFI, the log amp detectors and the beam current transformer. The video display is generated by the central micro.

8.2.6 System Software

Software developed for the interlock system may be divided into the following three groups:

Local Micro Software

- Monitors:
 - Gap status bits
 - Status of latches
 - BPM outputs (ADC)
- Compares:
 - BPM outputs from A and B interlocks and generates an alarm (background fault)
- Controls:
 - Gap inhibit override bits
 - Interlock branch test bits

Central Micro Software

- Monitors:
 - Status of interlock A and B latches
 - Status of latches in RFI
 - Background fault from each local node
 - Gap status from each local node
 - Log amp output and DCCT (beam current)
- Compares:
 - Outputs of log amps and DCCT and generates an alarm (background fault)
- Measures:
 - Delay from beam dump command to beam dump
- Controls:
 - Global inhibit (beam current) override
 - Beam dump command

Host Computer Software

BPM Calibration Programs:

- Measure transfer function= BPM output/local orbit bump amplitude input for each ID
- Measure BPM gains and offsets (using photon beam)

Pre-fill test:

- Checks operation of BPMs at each local node (clamp level)
- Checks operation of each branch of the interlock up to the last OR gate in CLC (both channels)
- Generates local orbit bumps in each insertion region to operate comparators and toggle status bits in LLC with global inhibit on, and to dump the beam with the global inhibit override
- Checks the operation of all latches in the RFI
- Generates a PASS/FAIL report for the machine operator prior to a high current fill for normal operations

Fault Report/Global Reset:

- Generates a report showing status of all latches and BPM readbacks after a bona fide beam dump
- Generates a global reset to clear all latches

8.3 Typical Operation

A typical operational cycle of the X-ray ring is shown in Fig. 8.3. As illustrated, an automatic test is performed at low current ($< 7\text{mA}$) prior to a normal fill for operations. As outlined earlier under "Software," this "pre-fill" test checks the status of each BPM, bumps the orbit in the ID regions to test the window comparators in the LLCs with the global low-current inhibit activated, and then overrides the global inhibit to dump the beam. If the pre-fill test, having checked all the necessary criteria generates a PASS report, the operator proceeds with a normal fill for operations.

Fig. 8.3 Typical Operational Cycle

At all times, each of the local micros and the central micro perform comparison tests between the A and B channels and between the log amps and the ring current DCCT. A fault in any of the background tests generates a warning to the machine operator. Calibration data for the BPMs etc. is generated during machine studies using photon beams.

Acknowledgements

The design of the system hardware and software evolved over a period of about a year with contributions from many individuals within NSLS as well as from other laboratories. Construction, installation and testing was performed by NSLS personnel.

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9 BUNCH LENGTHENING CAVITY FOR THE VUV RING

9.1 Introduction

The electron beam lifetime in the VUV Ring is limited by the loss of electrons due to intrabunch (Touschek) scattering. The loss rate due to the Touschek effect is proportional to the electron bunch density. Hence, in order to increase the beam lifetime we must reduce the bunch density. On the other hand, a key design feature of the VUV Ring is the achievement of high brightness of the photon sources by having an electron beam with small transverse beam dimensions. Therefore, to increase the beam lifetime without reducing the source brightness we have been led to the use of a fourth-harmonic RF cavity to increase the bunch length [9.1].

The main RF cavity operates at frequency $f_{RF} = 52.88$ MHz and the fourth-harmonic cavity at 211.5 MHz. The total voltage seen by the beam is

$$V(\phi) = V_0[\sin(\phi + \phi_s) + k \sin 4(\phi + \psi)] . \quad (9.1)$$

The angle $\phi = 2 \pi f_{RF} \tau$ is the phase angle with respect to the main RF frequency measured from the bunch center, Fig. 9.1. The angles ϕ_s and ψ are the synchronous phase angles for the main RF and the fourth-harmonic system. At the bunch center, the voltage is

Fig. 9.1 Wave form with the double RF system.

$$V(0) = V_o[\sin\phi_s + k \sin 4\psi] = U_o, \quad (9.2)$$

which must equal the synchronous radiation loss per turn U_o .

In order to lengthen the bunch, we want the phase and amplitude of the fourth harmonic cavity to be chosen such that the slope of the total RF waveform vanishes at the bunch center,

$$\frac{dV}{d\phi} = V_o[\cos\phi_s + 4k \cos 4\psi] = 0. \quad (9.3)$$

Ideally, we also desire the second derivative to vanish,

$$\frac{d^2V}{d\phi^2} = -V_o[\sin\phi_s + 16k \sin 4\psi] = 0. \quad (9.4)$$

It follows that

$$k = \frac{1}{4} \sqrt{\cos^2\phi_s + \frac{1}{16} \sin^2\phi_s}, \quad (9.5)$$

$$\psi = \frac{1}{4} \tan^{-1}\left(\frac{1}{4} \tan \phi_s\right), \quad \pi < 4\psi < 2\pi. \quad (9.6)$$

The total voltage is

$$V(\phi) = V_o[\cos\phi_s(\sin\phi - \frac{1}{4} \sin 4\phi) + \sin \phi_s(\cos\phi - \frac{1}{16} \cos 4\phi)], \quad (9.7)$$

$$V(0) = U_o = \frac{15}{16} V_o \sin\phi_s. \quad (9.8)$$

The equations describing synchrotron oscillations are [9.2]

$$\dot{\phi} = -\omega_{RF} \propto e/E_o, \quad (9.9)$$

$$\dot{e} = \frac{eV(\phi) - U_o}{T_o}, \quad (9.10)$$

where $\epsilon = E - E_0$ is the energy deviation from the synchronous energy, T_0 is the revolution period of the synchronous particle, α is the momentum compaction and $\omega_{RF} = 2\pi f_{RF}$. The longitudinal phase space distribution of the electron bunch is determined by the competition between the radiation damping and the quantum fluctuations. It can be shown, e.g. using the Fokker-Planck equation, that the equilibrium distribution has the Boltzmann form,

$$\lambda(\phi, \epsilon) = \frac{A}{\sigma_\epsilon \sqrt{2\pi}} e^{-\epsilon^2/2\sigma_\epsilon^2} e^{-b\Phi(\phi)} \quad (9.11)$$

where the energy spread σ_ϵ is independent of the potential function

$$\Phi(\phi) = \frac{\alpha}{E_0 T_0} \int_0^\phi d\phi' [eV(\phi') - U_0]. \quad (9.12)$$

Integrating over the Gaussian energy distribution, one determines the longitudinal bunch profile,

$$\xi(\phi) = A e^{-b\Phi(\phi)}. \quad (9.13)$$

In the case of a lengthened bunch, the first and second derivatives of voltage vanish, so $V(\phi) \sim \phi^3$ and, if the lengthened bunch is still short compared to the wavelength of the fourth harmonic cavity, then

$$\xi(\phi) = \xi_0 e^{-a\phi^4}. \quad (9.14)$$

9.2 The Fourth-Harmonic Cavity

A fourth-harmonic cavity operating at a frequency of 211.52 MHz was fabricated (Fig. 9.2). This all copper cavity has a $Q > 20,000$ and shunt impedance $R_s = 300 \text{ K}\Omega$. Since frequency stability was an important requirement, a regulated cooling system was purchased providing 10 gpm water flow through the cavity cooling channels. Cooling considerations were the main reason for choosing copper for the cavity structure.

The structure is a foreshortened re-entrant coaxial type resonator. The electromagnetic fields are shown in Fig. 9.3. The gap voltage is equal to $\int B \cdot ds$ (s is cross sectional area). Magnetic field, B , is maximum at the shorted wall, thus necessitating a good spring ring to carry 1500 amps when 50 kV is developed across the gap. The operating frequency was adjusted by shimming the nose cone. By varying the gap, g , the effective capacitance is changed. Since frequency is $1/(2\pi\sqrt{LC})$, this provides a convenient method for fine tuning. A computer code,

Fig. 9.2 Fourth harmonic cavity

Fig. 9.3 Electrician's representation of harmonic cavity.

superfish, provided sufficient dimensional accuracy that only 2 or 3-mm range was required for the gap adjustment. Spring rings provide RF contact between the nose cone and main body of the cavity. An aluminum heliflex ring provides a vacuum seal. It acts as a back-up in the event of spring ring failure since it also makes a good RF contact.

To provide remote frequency tuning, a motor-driven shorting loop is provided. A bellows is provided so the loop can be radially inserted into the cavity. The loop is water cooled due to high circulating currents. The advantage of this type of tuner is that only small capacitive displacement currents have to return to the cavity body. This eases the requirement of spring contacts on a moving body (Fig. 9.4). As the loop is inserted, the magnetic flux coupled from the main cavity increases. The short acts as a shorted turn on the secondary of a transformer, which reduces the primary flux and thus the primary inductance. This effectively increases the resonant frequency. Viewed from perturbation theory, a displacement of magnetic field increases the resonant frequency. A frequency shift of over 200 kHz is obtained.

Fig. 9.4 Frequency tuner of cavity

9.3 Passive Excitation of Bunch Lengthening Cavity

At present, we are running the bunch lengthening cavity passively, with the circulating electron beam self-exciting electric field in the gap. This approach has the advantage of simplicity over driving the harmonic cavity with an external generator. With an external generator, a stiff source is needed to maintain tight tolerances on the magnitude and phase of both RF systems, and generator-cavity--cavity-generator interaction is expected at higher currents. There are some limitations when running the harmonic cavity passively. Since it must be tuned to the Robinson unstable side of resonance, one must rely on damping from the main cavity to maintain stability. There is only one knob to tweak, hence the optimum potential (which depends on RF voltage amplitude and phase) is available at only one current and one tuner position. Implementation of an external generator would allow amplitude and phase control.

Here we shall describe the passive operation of the bunch lengthening cavity. Although the system is not yet optimized, we have doubled the lifetime in the VUV Ring at high current. To begin, let us consider the field excited in the harmonic cavity by a Gaussian bunch. For a Gaussian bunch, the time-dependence of the circulating current observed at a fixed azimuth of the storage ring has the Fourier expansion

$$I(t) = I_0 + 2I_0 \sum_{n=1}^{\infty} e^{-n^2 \omega_0^2 \sigma^2 / 2} \cos n\omega_0 t, \quad (9.15)$$

where I_0 is the average current of the bunch, ω_0 is the angular revolution frequency and σ is the rms bunch length. For the VUV Ring σ is less than 1 nsec, corresponding to a frequency of 1 GHz. The fundamental RF frequency 52.88 MHz is 9 times the revolution frequency 5.88 MHz. The revolution period is 170 nsec. The resonant frequency for the bunch lengthening cavity, 211.5 MHz, is 4 times the frequency of the main RF and 36 times the revolution frequency.

From the above, we see that the 211.5 MHz component of the current is approximately equal to the 52.88 MHz component. If there are several bunches, the components of the current at multiples of the main RF frequency add in phase, hence the 211.5-MHz current component is roughly equal to twice the average current in the ring. The average beam current can be as high as 1 amp. If the narrow band cavity is tuned to exactly 211.5 MHz, the beam self-excites a voltage of up to $R_s(2I_{av}) = (300 \text{ k}\Omega)(2 \text{ amp}) = 600 \text{ kV}$.

For single cavity operation the main cavity is run at 77 kV corresponding to a synchronous phase of 169° . To maintain the same synchronous phase with two cavities the main cavity should have a voltage of 82 kV and the harmonic cavity should be run at 20 kV. The corresponding value of 4ψ is -2.5° . Recalling that impedance is maximum at resonance, by detuning the cavity the amplitude of the generated voltage will decrease and its phase with respect to the current generator will approach $\pm 90^\circ$.

$$Z = R_s \cos\theta e^{-j\theta}$$

$$\text{Re}Z = R_s \cos^2 \theta; \text{Im}Z = R_s \cos\theta \sin\theta$$

$$\tan \theta = 2Q \Delta\omega/\omega_r$$

where $\theta = -(90 + 4\psi)$.

By tuning the cavity above the generator driving frequency a voltage of 20 kV can be achieved even when the average current is 1 amp.

$$\theta \approx -90^\circ, \text{Im}Z \approx \frac{20 \text{ kV}}{2 \text{ amp}} = 10 \text{ k}\Omega,$$

$$\theta \approx \cos^{-1}\left(\frac{\text{Im}Z}{R_s \sin\theta}\right) \approx \cos^{-1}\left(\frac{10 \text{ k}\Omega}{300 \text{ k}\Omega}\right) \approx -87.5^\circ,$$

$$\text{Re}Z = 300 \text{ k}\Omega \cos^2 \theta = 570 \Omega,$$

$$P_{\text{loss}} = \frac{(\text{Re}Z)(2I_{av})^2}{2} = \frac{(570 \Omega)(4 \text{ amp}^2)}{2} = 1140 \text{ W},$$

$$I_{av}U_o = (1 \text{ amp})(14 \text{ keV}) = 14 \text{ kW},$$

$$\Delta f = \left(\frac{\tan \theta}{2Q}\right)f_r = \left(\frac{\tan -87.5^\circ}{40,000}\right)(211 \times 10^6 \text{ Hz}) = -121 \text{ kHz}.$$

To get ideal debunching there is only one current at which the phase and amplitude of the beam-induced signal can result in a net zero slope. Even this is difficult to achieve for the following reasons.

(a) Though the voltage phase angle may be correct, it would be necessary to adjust the harmonic cavity Q to arrive at the proper magnitude of voltage. For the example given the shunt impedance would have to be reduced from 300 to 47 k Ω .

$$|Z| = 47 \text{ k}\Omega [(\cos^2 87.5^\circ)^2 + (\cos 87.5^\circ \sin 87.5^\circ)^2]^{1/2} = 10 \text{ k}\Omega$$

(b) At the current specified there is an additional power loss introduced by the harmonic cavity. This would modify the nominal synchronous phase. As circulating current decreases, the departure from the nominal phase decreases since harmonic cavity voltage decreases (not linearly).

(c) It will be shown that for stability the harmonic cavity has to be run at an amplitude slightly below ideal.

Nevertheless we have succeeded in experimentally improving the lifetime by more than a factor of 2. The detuning is fixed (see Fig. 9.5) and the ring is charged to full current. Since Touschek is most detrimental at higher currents, the detuning is set for the desired voltage of 20 kilovolts at 1 amp. As the beam current decreases the self induced voltage decreases. Even though the proper voltage is not maintained at lower currents, we still see lifetime improvement over the entire decay of the stored beam. The observed profile of the lengthened bunch is shown in Fig. 9.6.

Fig. 9.5 Typical fill decay vs. time (a) without and (b) with harmonic cavity.

Fig. 9.6 Longitudinal profile: (left) single cavity; (right) dual cavity.

It should be noted that by coupling a resistive load to the cavity by a magnet loop the Q of the harmonic cavity can be reduced, thus increasing the current at which the ideal voltage is obtained.

If the 4th-harmonic cavity voltage is too high the potential well forms two pockets (Fig. 9.7). The phase diagram corresponding to the distorted potential well is shown in Fig. 9.8. Note that a particle at synchronous energy can exist at three points, namely τ_0 and $\pm\tau_1$. Particles with energy deviation $\epsilon < \epsilon_c$ will be trapped in an orbit centered around either $+\tau_1$ or $-\tau_1$. When $\epsilon = \epsilon_c$ the particle will travel in a path that appears as a separatrix and can jump back and forth between the $\pm\tau$ regions. When $\epsilon > \epsilon_c$ the path will be symmetrical around τ_0 . We are fairly confident this distortion initiates an instability but we are not certain of the mechanism. At present, we run just below the optimum detune position to assure stable operation.

From fill to fill the bunch profile changes and is dependent upon how many bunches are filled. For evenly spaced bunches each bunch has the same shape. For unsymmetric fills bunch to bunch shapes change. When 1, 3 or 9 bunches symmetrically fill the 9 buckets, the sidebands are generated. If there is any induced voltage due to these sidebands, each bunch will cross the cavity gaps at the same phase with respect to this induced voltage. This is not true for the other bunch patterns, and the potential well distortion, due to these voltages, would be different for each bunch. This could account for different bunch shapes when the buckets are not filled symmetrically.

In conclusion, a self-excited harmonic cavity is in operation at the VUV ring and has improved lifetime by a factor of two. We expect further improvement in the future. The effects of over-excitation of the harmonic cavity, Robinsons instability [9.3], and changes of beam shape from fill to fill are being studied. The addition of an RF harmonic power source will be pursued with the hope of optimizing the voltage waveform during the entire fill [9.4].

(a) Energy vs. phase

(b) Resultant potential well

Fig. 9.7 Potential when harmonic cavity voltage is excessive.

Fig. 9.8 Phase diagram showing distorted well

Acknowledgements

Frequent discussion with J.M. Wang were invaluable. In addition I want to recognize the work of Jonathan Wachtel on this project and Richard Biscardi for implementation of the bunch-lengthening system.

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Fig. 8.2 Block Diagram of System

8.2.2 Local and Global Inhibits

To permit testing of the individual blocks and of the overall system, local as well as global inhibit functions have been incorporated in the design. A local node may be automatically inhibited either if the gap of the insertion device is open or if

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10 SXLS STORAGE RING DESIGN

10.1 Introduction and Source Specifications

X-ray lithography [10.1] has emerged as a strong candidate to meet the demands of ever finer linewidths on integrated circuits, particularly for linewidths less than .25 microns. Proximity printing X-ray lithography makes use of soft X-rays to shadow print an image of a mask onto a semiconductor wafer to produce integrated circuits. To generate the required X-rays in sufficient quantities to make commercial production viable, electron storage rings have been proposed as the soft X-ray sources. Existing storage rings have been used to do the initial development work and the success of these efforts has led the lithographers to request that new rings be constructed that are dedicated to X-ray lithography [10.2].

As a result of a series of workshops held at BNL [10.3] which were attended by both semiconductor and accelerator scientists, the following set of 'zeroth order specifications' on the light and electron beam of a storage ring for X-ray lithography were developed:

- critical wavelength of light: $\lambda_c = 6$ to 10 angstroms,
- white light power: $P = 0.25$ to 2.5 watts/mrad,
- horizontal collection angle per port: $\theta = 10$ to 50 mrad,
- electron beam sizes: $\sigma_x \approx \sigma_y < 1$ mm,
- electron beam vertical angular spread: $\sigma'_y < 1$ mrad.

10.2 Design of Electron Storage Rings for X-Ray Lithography

The gross parameters of an electron storage ring to meet the above requirements can be obtained from the following formulas where E and I are the energy and current of the electrons, B and ρ are the dipole field strength and bending radius and C is the circumference of the ring:

$$E[\text{GeV}] = .3 B[\text{T}] \rho[\text{m}], \quad (10.1)$$

$$\lambda_c[\text{\AA}] = \frac{18.64}{B[\text{T}] E^2 [\text{GeV}]}, \quad (10.2)$$

$$P[\text{w/mrad}] = \frac{0.0787 E [\text{GeV}] I [\text{ma}]}{\lambda_c[\text{\AA}]}, \quad (10.3)$$

$$C = 2\pi\rho + L_{\text{quads}} + L_{\text{drifts}} + L_{\text{sexts}}. \quad (10.4)$$

Conventional electromagnets are limited to fields of about 1.5 Tesla whereupon the saturation of the iron yoke becomes a problem. Superconducting magnets can be used to produce much higher fields of about 4 Tesla at the price of a more complicated magnet. With these constraints on the magnetic field the possible storage rings bifurcate quite naturally into two classes, one based on conventional magnets, the other on superconducting magnets. Typical parameters of the two types of machines are given in Table 10.1.

Table 10.1 Typical Parameters of Conventional and Superconducting Magnet Storage Rings Design for X-Ray Lithography.

	Magnet	
	EM	SC
B [T]	1.5	4
E [GeV]	1.1	.68
λ_c [Å]	10	10
ρ [m]	2.4	.56
C [m]	25-50	8-15
I [ma]	200	300

Conventional magnet rings have the advantage that they are based on well established technology which should provide high reliability and they could be made available in roughly the time it takes to build them (≈ 2 years). These rings will have a circumference in the range of 25 to 50 meters. For a fixed critical wavelength, conventional magnet rings require 30% less current than cold magnet rings to achieve a desired flux because the rings operate at a higher energy.

At the present time (February 1991) the semiconductor industry has shown a preference for the smaller 'footprint' of the SC machine, $C \approx 8-15$ m.

10.3 The SXLS Project at the NSLS

In March 1988 the Superconducting X-Ray Lithography Source (SXLS) project at the National Synchrotron Light Source at Brookhaven was initiated with funding from the Defense Advanced Research Projects Agency (DARPA). The goal of the SXLS Project is to design and construct a compact storage ring of circumference $C = 8.5$ meters. It will use superconducting dipoles with a field of $B_0 = 3.87$ Tesla and a bending radius of $\rho = 0.6037$ meters along with 700 MeV electrons to produce 10-Å X-rays for proximity printing lithography. An additional goal of the project is to transfer the technology of how to build the machine to US industry. The Grumman Aerospace Corporation and General Dynamics have been selected as the industrial collaborators.

The project is proceeding in two phases. In Phase I the machine is being constructed with low field iron dipole magnets, $B_{\max} = 1.1$ Tesla, with the same bending radius as the superconducting magnets [10.4]. With these low field dipoles the energy of the machine will be limited to $E_{\max} \leq 200$ MeV. For Phase II, the low field dipoles will be replaced with superconducting magnets to enable the ring to reach energies of $E = 700$ MeV and generate $10 \text{ \AA}$ photons for lithography.

10.4 SXLS Storage Ring Lattice

In this section we discuss several possible lattices that were considered for the SXLS ring and give an overview of the machine.

10.4.1 One 360° Dipole Machine

To achieve the smallest possible circumference in a storage ring the only candidate is a ring consisting of one 360° combined function dipole magnet. A weak focusing ring of this type named AURORA [10.5] has been constructed by Sumitomo Heavy Industries in Japan. The machine has been successfully commissioned and is capable of operating with 300 mA at an energy of 650 MeV.

For a weak focusing machine of the AURORA type an analytic expression for the electron beam sizes can be given in terms of the field index, n , the bending radius, ρ and the electron energy [10.2],

$$\sigma_x[\text{mm}] = 2.1 E[\text{GeV}] \left[\frac{\rho [\text{m}]}{n(3-4n)} \right]^{1/2}. \quad (10.5)$$

For typical values of the field index, $0 < n < .75$, this leads to horizontal electron beam sizes in the range of 1 to 2 mm. Since these beam sizes exceed the specifications given in Section 10.2 we did not adopt this type of structure for the SXLS ring. In addition it is difficult to include all the necessary accelerator hardware in a cramped ring of this type.

10.4.2 Two 180° Dipole Lattices

To lower the beam size the dipole magnets must be split into more pieces and quadrupoles must be added to reduce both the emittance and the dispersion. Splitting the magnet into more pieces also makes it easier to include the other necessary hardware such as the RF cavity, injection kickers, diagnostics, etc. Fig. 10.1 displays three possible lattices consisting of two dipoles and a minimum number of quadrupoles. Other two-dipole lattices have been discussed in the literature but they contain more magnetic elements [10.6, 10.7].

The lattice A, which was adopted for the COSY ring [10.8], has two super-periods but it does not have reflection symmetry about the center of the dipole

Fig. 10.1 Some Possible Two-Dipole Lattices

magnet. The Twiss parameters for such a lattice with $\alpha \neq 0$ and $\eta' \neq 0$ in the center of the dipole will result in a higher emittance than the symmetric lattices B and C. Concerns on satisfying the beam size requirements and a preference for a symmetric lattice with a higher momentum compaction led us to consider lattices of types B and C.

The symmetric lattices B and C are actually very similar. One has a longer straight section which facilitates the positioning of the injection hardware and the RF cavity but at the expense of locating the quadrupoles closer to the strong fringe field of dipoles magnets. A lattice of the B type was adopted for the HELIOS machine being constructed by Oxford Instruments for IBM [10.9,10.10]. A slight variant of the type C lattice with the central quad split in two to accommodate a focussing sextupole was proposed and adopted by Vignola for the SXLS ring [10.11].

Since the type B and C lattices contain only focusing quadrupoles there must be a gradient in the dipole magnet to provide betatron stability in the vertical plane. An interesting feature of these lattices, in which the dipole magnet has a field index less than unity ($n < 1$), is that in the horizontal plane there are no defocusing elements (both the quadrupoles and the dipoles are focusing elements). This is what allows the horizontal betatron tune (ν_x) to exceed unity in a FODO-like machine with only two superperiods. The vertical plane is like a traditional FODO cell with alternating defocusing (quads) and focusing elements (combined function dipoles).

One undesirable characteristic of these lattices is that there is roughly 180° of horizontal betatron phase advance inside the dipole magnet. Such a large phase advance "trapped" inside the dipole magnet complicates the closed-orbit correction.

To correct the chromaticity, horizontally focusing sextupoles are located between the quads and a defocusing sextupole is incorporated into the pole shape of

the dipole magnet. To be able to trim the vertical tune and chromaticity, two sets of poleface windings have been included on the dipole magnet in the Phase I ring and separate trim coils will be included in the superconducting dipole in the Phase II machine. For orbit correction the quadrupole magnets are mounted on translation stages which can be moved horizontally and vertically by ± 3 mm. There are air core dipole trim magnets and in addition, in the Phase I ring, there are twelve pole magnets located just outside the dipole magnets to provide additional trimming capability.

The main parameters of the SXLS ring are listed in Table 10.2 and a schematic drawing of the Phase I storage ring is shown in Fig. 10.2. The Twiss parameters for the ring are given in Fig. 10.3.

Table 10.2 SXLS Storage Ring Parameters.

	Phase I	Phase II
Energy, E [MeV]	200	700
Dipole Magnet Type	EM	SC
Dipole Field, B_0 [T]	1.1	3.87
Bending Radius, ρ [m]	.6037	.6037
Field Index, n	.1759	.1759
Superperiods, N_s	2	2
Circumference, C [m]	8.503	8.503
Critical Wavelength, λ_c [Å]	423	10
Horizontal Betatron Tune, ν_x	1.415	1.415
Vertical Betatron Tune, ν_y	.415	.415
Energy Loss Per Turn, U_0 [KeV]	.234	34.4
Uncorrected Chromaticity, ξ_x, ξ_y	-.49, -1.32	-.49, -1.32
Momentum Compaction, α	.32	.32
Natural Emittance, ϵ_0 [m-rad]	5.92×10^{-8}	7.17×10^{-7}

Fig. 10.2 SXLS Phase I Storage Ring

Fig. 10.3 SXLS Twiss Parameters

10.5 Status of the Phase I Storage Ring

The construction of the Phase I ring was completed in August 1990 and commissioning of the storage ring began in early September 1990. The design current of 500 mA in six bunches was achieved in December 1990 using the 200-MeV injection system of the NSLS.

In February 1991 the ring was injected at 80 MeV for the first time and 160 mA were accumulated. Studies will continue on the machine for the next year to improve our understanding of the ring.

Although the photons from the Phase I ring ($\lambda_c = 423 \text{ \AA}$) are not suitable for proximity printing lithography which requires 6 to 10- $\text{\AA}$ photons, a slight variation of such a ring could serve as a source of 130- $\text{\AA}$ photons for projection X-ray lithography [10.12].

10.6 Superconducting Magnet Design

In Phase II of the SXLS project the two 180° bending magnets will be replaced by air-core superconducting dipoles. The nominal vertical field of the dipoles is 3.87 T which is achieved by three pairs of superconducting coils (see Fig. 10.4). Detailed magnetic field calculations were carried out to optimize the coil configurations to obtain the specified multipole components of the field while satisfying various mechanical design constraints [10.13]. Several trim coils have been included in the design for independent adjustment of the field components. This section is a discussion of a novel application of Berz's Differential Algebra package [10.14] to the computation of multipole coefficients and coil position tolerances in an air core magnet [10.15].

Fig. 10.4 SXLS Superconducting Dipole Coils

For the complicated coil geometry given in Fig. 10.4 the magnetic field is truly a three-dimensional animal, the curvature of the magnet is large ($\rho = 60$ cm) and for an air-core magnet the field is nonisomagnetic. For simplicity we confine our discussion to magnets possessing midplane symmetry. The general expression for the magnetic field in curvilinear coordinates is given by Brown and Servranckx [10.16]; for our purposes it suffices to write out the expression only to second order in x and y , where

$$B_x(x,y,s) = A_{11}y + A_{12}xy + \dots \quad (10.6)$$

$$B_y(x,y,s) = A_{10} + A_{11}x + \frac{1}{2!} A_{12}x^2 + \frac{1}{2!} A_{30}y^2 + \dots \quad (10.7)$$

$$B_s(x,y,s) = \frac{1}{(1 + hx)} [\dot{A}_{10}y + \dots] \quad (10.8)$$

where $A_{1,n}(s) = \partial^n B_y(s) / \partial x^n$, $A_{30}(s) = -\ddot{A}_{10} - A_{12} - hA_{11}$, $\dot{A}_{10} \equiv dA_{10}/ds$ and $h = 1/\rho(s)$.

The coefficients $A_{1,n}(s) = \partial^n B_y(s) / \partial x^n$, are the multipole coefficients widely used in accelerator physics, e.g., $A_{10} \equiv$ dipole, $A_{11} \equiv$ quadrupole and $A_{12} \equiv$ sextupole, etc. There are two other types of terms in the above equations: non-isomagnetic terms, for example $\dot{A}_{10}$, and combined function feed-up terms, hA_{11} .

The magnetic field in an air-core magnet is given by the Biot-Savart law,

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} \int d^3r' \frac{\vec{J}(\vec{r}') \times (\vec{r} - \vec{r}')}{|\vec{r} - \vec{r}'|^3}, \quad (10.9)$$

where $\vec{J}(\vec{r}')$ is the current density in the conductor and $\vec{r}$ is the observation point.

For a given coil configuration the field in principle can be computed to machine precision since there is no complicated meshing of the problem as is necessary in an iron magnet. The difficulty remains in obtaining the correct multipole coefficients from knowledge of the magnetic field at each point in space.

Several methods to obtain the multipole coefficients have been used in the past:

1. Numerical finite differencing to compute derivatives,
2. Fitting of the pointwise field data by polynomials,
3. FFT of the field on a circle surrounding the reference trajectory.

Each of the methods suffers from serious drawbacks for non-isomagnetic combined-function bending magnets. The first method yields unacceptable results for all but the lowest-order multipole coefficients. The problems encountered with fitting data are as follows:

1. How many data points should be used?
2. Over what range in $\pm x$ or y should be used?
3. What is the maximum order of the polynomial to be used?

Finally, the FFT method, which is best suited for straight multipole elements, runs into trouble with the non-isomagnetic and combined-function feed-up terms.

What is really desired is to be able to obtain a Taylor series expansion of Eq. (10.9) in x, y and s directly. This is precisely what the DA package can do. The DA package can produce an arbitrary-order Taylor series with respect to any of the variables x, y or s . In this way the multipole coefficients are obtained without any of the problems associated with the above methods.

The DA package can also be used to compute the effects of coil positioning errors on the various multipoles by producing a Taylor series of $\vec{B}$ with respect to the position of the coils that serve as limits to the integrals in Eq. (10.9). Such a tool is very valuable to set limits on the errors during the mechanical construction of the magnet.

The coils in the SXLS air-core superconducting magnet are constructed of arcs or straight sections of rectangular cross section. In this case the integrals in Eq. (10.9) over the cross section of the coils can be carried out in closed form; the remaining integral over the angular extent of the coil is computed numerically [10.17]. We have written a computer code to perform these magnetic field calculations and "DA-ed" it to be able to compute the desired multipoles throughout the magnet $[A_{1,n}(s)]$ and the changes in these multipoles due to positional errors in the coil placement [10.18].

10.7 Multiturn Particle Tracking For SXLS

Once the chromaticity of the ring has been corrected and the additional nonlinear multipole content of the dipole magnets is known one must be able to numerically track particles for many turns in the ring to see if they are stable; the quest for the so-called dynamic aperture. Unfortunately most of the existing "tracking codes" have been written to model large accelerators ($\rho \gg 1$) with separated-function bending magnets ($hA_{11} = 0$, etc). The approximations to the particle dynamics in these codes render them inappropriate for tracking in machines such as SXLS.

In constructing a model for tracking one should include the following concepts:

- Canonical variables: $(x, p_x, y, p_y, \tau, \delta)$,
- Kinematic nonlinearities: e.g., p_x^4, hxp_x^2 ,
- Combined function feed-up terms: e.g., hA_{11} ,
- Symplectic tracking,
- Normal form map analysis,
- Nonisomagnetic fields, e.g., $\dot{A}_{10}$.

A new tracking code, dubbed KRACKPOT, which incorporates the first five items in the above list, has been developed [10.15, 10.19]. In essence it is a "kick" code based on the symplectic integrator concept of Forest and Ruth [10.20]. The tracking module is linked to Berz's DA package to provide for the generation of arbitrary-order Taylor series or Lie polynomial maps. In KRACKPOT, the tracking is done using the "explicit" symplectic integrator and not maps, although map tracking is also possible. The normal-form analysis tools can be applied to the maps to extract such things as tunes, chromaticities and geometric tune shifts with betatron amplitude [10.21]. The virtue of KRACKPOT over existing codes is that it properly addresses isomagnetic combined-function bending magnets with arbitrary-order nonlinearities and magnet bending radius. Work is continuing to include the effects of non-isomagnetic fringe fields.

Acknowledgements

I would like to express my gratitude to my colleagues in the SXLS project. In particular the key role played by Gaetano Vignola (INFN) during the design of the machine is gratefully acknowledged. The work on symplectic integrators and the use of the DA tools was made possible by a very fruitful collaboration with Etienne Forest (LBL-ESG) and Michael Reusch (Gumman Aerospace Corporation).

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