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Optimization of a Synchrotron Radiation Source*

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MASTER

Abstract

Some aspects of the optimization of an electron storage ring as a synchrotron radiation source will be presented. This will include the choice of magnet ring structure, choice of electron accelerating system parameters and choice of structure sections for the use of high field wigglers or undulators.

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Introduction

The very pronounced growth of the utilization of synchrotron radiation for research in the domain of the material sciences, atomic and molecular physics, biology and technology has led to the construction of a new generation of high current electron storage rings dedicated solely to the usage of the emitted synchrotron radiation. As a consequence it became feasible, in the design stage, to optimize the ring structure, as a multiple photon port structure with optimized optical characteristics, rather than, typically, an optimized structure for e^+e^- colliding beams dedicated to high energy particle physics research. For example, the deleterious effect due to non-linear tune shifts associated with the interaction of the two beams in a colliding beam facility puts a limit on the minimum vertical beam emittance desirable in order to obtain maximum interacting beam luminosity. For a single beam synchrotron radiation source, minimum emittances are desirable in order to obtain optimum source brightness. It is possible to achieve this by optimizing specifically the storage ring lattice structure so that maximum damping (associated with the emission of the synchrotron radiation) of the transverse betatron oscillations occurs.

Also, in a "conventional" e^+e^- colliding beam storage ring or electron synchrotron, the choice of maximum dipole field value is guided principally by the desire to minimize the total synchrotron radiation power emitted and generally low field values are adopted. With the desire for high flux, high photon energy synchrotron radiation sources it is more favorable to adopt high dipole field values in the orbit lattice structure. This may be further enhanced by incorporating very high field (superconducting magnet) devices at a number of specific locations in the storage ring. The inclusion of these so-called orbit wigglers and the optimization of the associated

synchrotron radiation sources introduces new constraints on the electron ring lattice structure, which can be met optimally only in the basic design of a (dedicated) synchrotron radiation source.

In the following a few specific aspects entering into the optimization of an electron storage ring as a synchrotron radiation source will be dealt with.

Synchrotron Radiation Source Definition

The basic relationship correlating photon source brightness and electron beam parameters has been worked out by Green¹ and can be expressed as:

$$B(X = X' = Y = Y' = 0) = N_k(0, \lambda) / 2\pi \sigma_x \sigma_y \quad \text{with}$$

$$N_k(0, \lambda) = 3.46 \cdot 10^{15} k I \gamma^2 H_2(\lambda_c / \lambda) \quad \text{Ph./sec, } k\lambda, d\psi, d\theta$$

$$\text{and } H_2(\lambda_c / \lambda) = (\lambda_c / \lambda)^2 K_{2/3}^2(\lambda_c / 2\lambda) \quad , \quad k = \Delta\lambda / \lambda$$

where X, X', Y, Y' refer to the components of the (four dimensional) photon beam phase space and σ_x, σ_y are the electron beam transverse dimensions.

This expression is valid, in first approximation, for an azimuthally limited length source, at or near a beam "waist" location, with the condition that $\sigma_y < \sigma_r$ and $\sigma_{x'} < \sigma_r$ where $\sigma_r \approx 0.56 \gamma^{-1} (\lambda / \lambda_c)^{0.43}$, is the natural opening angle of the synchrotron radiation. From this expression it follows that maximum source brightness is obtained for minimum values of σ_x, σ_y ($\sigma_{x'}, \sigma_{y'}$) or minimum emittance values ϵ_x, ϵ_y of the electron beam (note $\sigma_x = \sqrt{\epsilon_x \beta_x}$).

Although, in general, maximum source brightness is desirable, such as for experiments requiring small angular spread on a small sample, as for example in protein crystallography, there are a number of experimental arrangements, whereby only the two dimensional phase space photon flux density is of importance, e.g. whereby with the use of slits the resolving power of a monochromator is improved. Depending on the use of an imaging element between the synchrotron radiation source and, typically, the monochromator entrance slit, the transmitted photon flux through the entrance slit is given by¹

$$N_s \sim N_{hv} d_s / (\sigma_r^2 + \sigma_y^2)^{1/2} \quad \text{or}$$

$$N_s \sim N_{hv} d_s / M_s (\sigma_y^2 + \ell_s \sigma_r^2)^{1/2} \sim N_{hv} d_s / M_s \sigma_y \quad \text{where}$$

M_s is the optical (de)magnification factor, d_s is the slit width and ℓ_s is the azimuthal source extent. Since for a multiplicity of beam lines it is desirable to be able to optimize the transmitted photon flux in either case, it is desirable, from a synchrotron radiation source optimization point of view, to minimize both σ_y and σ_r simultaneously, hence to minimize the beam vertical emittance, ϵ_y . For a practical electron storage ring magnet structure the vertical beam emittance is determined by the magnitude of radial-vertical coupling of the betatron motion, which results in a typical magnitude of $\epsilon_y \sim 10^{-2} \epsilon_x$ (i.e. it is difficult to reduce the coupling coefficient below ~ 0.1). As a consequence, in practice, minimum vertical beam emittance is obtained with the reduction of the horizontal beam emittance. Therefore, also in this case maximum source brightness (simultaneous

reduction of ϵ_x, ϵ_y) is the relevant criterion for optimum synchrotron radiation source design.

Electron Storage Ring Structure

The beam emittance ϵ_x (and "coupled" with this ϵ_y) in an electron storage ring is the result of the longitudinal and transverse oscillation amplitude damping associated with the mean energy loss due to the emission of synchrotron radiation, limited by the random excitation of the oscillation amplitudes due to the discrete quantum nature of the photon emission. Its equilibrium value is dependent on electron beam energy and the parameters of magnet ring structure. The analysis of the relationship of the beam emittance and storage ring lattice structure parameters may be found in Sands². From this, assuming a well aligned magnet structure and no momentum dependent effects:

$$\epsilon_x = C_q \gamma^2 I_5 / (I_2 - I_4), \quad \epsilon_y = k^2 \epsilon_x \quad \text{with}$$

C_q , a constant and the synchrotron radiation integrals, I_1 , defined as $I_5 = \oint H G^3 ds$, $I_2 = \oint G^2 ds$, $I_4 = \oint \eta G^3 ds$, [$I_1 = \oint \eta G ds$, $I_3 = \oint G^3 ds$] where H is the dispersion function invariant* $H = \bar{\gamma} \eta^2 + 2 \bar{\alpha} \eta \eta' + \bar{\beta} \eta'^2$ with $\eta(s)$, the electron orbit dispersion function and $G(s)$, the curvature function.

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* Analogous to the Courant-Snyder invariant, however, H is invariant only through drift spaces and focusing elements of the lattice, it changes through dipoles.

For a separated function, iso-magnetic, storage ring the curvature function $G(s) = 1/\rho$, resulting in $I_5 = (\oint H ds)/\rho^3$; $I_2 = 2\pi/\rho$; $I_4 = 2\pi\alpha_p R/\rho^2$ with ρ the magnetic bending radius and $\alpha_p = (\Delta C/C)(\Delta p/p)$, the storage ring momentum compaction function. Since $\alpha_p \ll 1$ it follows that

$$\epsilon_x \approx C_q \gamma^2 [(\oint H ds)/2\pi\rho^2].$$

The bracketed part is dependent on the magnet structure parameters only, therefore, for various synchrotron radiation structures, designed for different electron beam energies (γ), a "figure of merit" characterizing the storage ring lattice structure may be defined, given by

$$(\oint H ds)/\rho^2$$

This quantity has been evaluated for a number of storage ring structures either in existence or under construction at the present time for dedicated synchrotron radiation sources. This is summarized in Fig. 1 where the lattice structure functions are given for these sources together with the magnitude of the lattice figure of merit. For lower energy storage rings the latter quantity tends to be larger because the objective of small ϵ_x (and ϵ_y) must be balanced, for economical reasons, by the objective of highest photon energy ($\epsilon_{crit} = C_1 \gamma^3/\rho$) for a particular structure, without going to higher electron energy ($P_{rf} = C_2 \gamma^4/\rho$), i.e. a shift to shorter wavelengths is obtained with the use of smaller ρ values in the magnetic structure. While taking this aspect into account, it follows, however, that a superior synchrotron radiation source lattice structure is obtained for a ring for which $\oint H ds$ has a minimum value. This is optimally achieved by use of basic achromatic bend sections separated by zero momentum dispersion sections. An added requirement at the origin location of the source is the need for minimum β values for optimum local source brightness. This combination of

FIGURE 1. STRUCTURE COMPARISON OF SOME REPRESENTATIVE SR SOURCES

SPEAR, 3 GeV, e^+e^- , "FODO"

PHOTON FACTORY, 2.5 GeV, SR, "FODO"

ALADDIN, 1 GeV, SR, "DOUBLET"

NSLS, 2.5 GeV, SR, "TRIPLET-ACHRO.B."

criteria has been met successfully, with a minimum number of magnet components in the design of the NSLS storage rings,^{3,4} of which the x-ray lattice, together with basic parameters, is given in Fig. 2.

Choice of Electron Accelerating System Parameters

For dedicated synchrotron radiation sources, a number of storage ring optics operational modes are of interest. In case of high resolution spectroscopy a high brightness source (four dimensional phase space density, $N_{hv}/\sigma_r^2 \sigma_x \sigma_y$) is desired. This, as shown above, requires a small ϵ_x or β_{ds} value. This tends to result also in a small momentum compaction, α_p , value, with as a consequence a smaller bunchlength ($l_b \propto \alpha_p^{-1/2} f^{-1}$, see below). As a result a high volume density is obtained ($I/\sigma_x \sigma_y \sigma_r$), which limits the source brightness lifetime because of the so-called Touschek effect, a loss of particles from longitudinal phase stability due to intrabunch electron scattering. In this case a lower rf frequency value for the electron accelerating system would be favorable since this promotes larger bunch length values. Alternatively, for dynamic measurements, using synchrotron radiation sources, sample illumination duration is of importance. Typically, for fluorescent lifetime measurements bunch length values as low as 0.1 nsec (or $l_b \sim 3$ cm) may be desired in specific cases, possibly at a cost in total photon flux available in order to maintain acceptable source brightness lifetime. Consequently, factors affecting bunch length are of interest here, such as rf parameters, use of harmonic accelerating cavity, lattice structure parameters, etc. Extending now the work by Saxon and Schwain⁵ on the choice of the rf frequency for the Daresbury storage ring, a few relationships are given here separating out specifically the bunch length dependency on structure parameters and on rf parameters.

The electron beam bunch length, for equilibrium energy spread

is given by²:

$$l_b = 2c\sigma_r = (c \alpha_p / \pi f_s) (\sigma_\epsilon / E)$$

FIGURE 2

2.5 GEV LATTICE STRUCTURE OPTIMIZED AS A
SYNCHROTRON RADIATION SOURCE

$$P_M = 6.9 \text{ M}; \hat{B} = 1.2 \text{ T}; L_B = 2.7 \text{ M}; C = 170 \text{ M}$$

$$v_x, v_y = 9.7, 5.7; \alpha_n = 0.0065$$

$$\begin{cases} \epsilon_x = 8 \cdot 10^{-8} \text{ M.RAD.} \\ \epsilon_y = 8 \cdot 10^{-10} \text{ M.RAD.} \\ (\sigma_\epsilon/E) = 8.2 \cdot 10^{-4} \end{cases}$$

where σ_τ is the bunch duration, f_s is the synchrotron oscillation frequency and (σ_ϵ/E) is the standard deviation energy spread of the bunch. The quantity f_s is given by

$$f_s = f (\alpha_p V \cos \varphi_s) / (2\pi h E)$$

where f is the frequency of the electron accelerating field, h is the harmonic number (number of possible bunches in the ring), V is the rf voltage amplitude and φ_s is the synchronous phase angle. It is of interest now to separate bunch length dependency on lattice structure parameters and on the accelerating system parameters. This is simply done by making use of the expressions for the synchrotron radiation integrals. It follows:

$$l_b = \left[\frac{4ec}{(mc^2)^2} \frac{C_q}{C_\gamma} \right]^{\frac{1}{2}} \cdot \left[\frac{I_1 I_3}{I_2 (2I_2 + I_4)} \right]^{\frac{1}{2}} \cdot \left[\frac{1}{f^{\frac{1}{2}} (q^2 - 1)^{\frac{1}{4}}} \right] \cdot \frac{1}{E^{\frac{1}{2}}} \text{ where}$$

$$C_q = 3.8 \cdot 10^{-13} \text{ m}; C_\gamma = 8.85 \cdot 10^{-5} \text{ m GeV}^{-3}; q = (eV/U_0) = (\sin \varphi_s)^{-1}$$

with U_0 the synchrotron radiation loss per orbit and q the rf overvoltage factor;
or

$$l_b = \text{Const. } C_{\text{structure}} \cdot F_{\text{rf}} \cdot E^{-\frac{1}{2}} \text{ where}$$

$$F_{\text{rf}} = f^{-\frac{1}{2}} (q^2 - 1)^{-\frac{1}{4}}.$$

A relationship $q = F(f)$ may now be found by considering the following: The quantum nature of the energy loss due to synchrotron radiation requires a large phase stable "bucket" area in order to prevent electron loss from the longitudinal phase stable area. A "quantum life time" may be associated with this loss process. Demanding now a (minimum) life time value of $\tau_q = 100$ hrs, the magnitude of q may be quantized², and leads to a relationship $q = F(f)$, which for values of $q > 1$ can be approximately written (for specific isomagnetic-separated function lattice structures) as:

$$q \approx C_1 (\alpha_p R/E) f + C_2$$

indicating the need for larger rf overvoltage factors when using higher accelerating frequency values (typical: NSLS; $f = 50$ MHz, $q \approx 1.3$; SRL; $f = 500$ MHz, $q \approx 7.5$). As a consequence now, an approximate expression for λ_b may be written as:

$$\lambda_b \approx \text{Const.} \cdot C'_{\text{structure}} \cdot f^{-1} E^{-1/2}$$

stating the inverse proportionality of bunch length and frequency of the accelerating system. This is further illustrated in Fig. 3 where it is indicated that a choice of a low accelerating frequency value would be unacceptable from the point of view of dynamic spectroscopy unless this would be matched with an optimized design of the storage ring lattice structure (typical calculated values (ignoring bunch "blow-up": NSLS; $f = 50$ MHz; $2\sigma_T$ ($q = 1.3$) ≈ 0.35 nsec; PF, $f = 500$ MHz, $2\sigma_T$ ($q \approx 4.5$) ≈ 0.13 nsec). With a lower frequency choice, a higher overvoltage factor than that required for acceptable quantum lifetime is readily achievable, reducing thereby further the bunch length value. In addition, by suitable use of a harmonic rf cavity a further reduction of bunch length can be achieved.

The choice of accelerating frequency has further specific consequences in terms of the minimum shunt impedance of the accelerating structure (higher q value or higher frequency unfavorable); the beam induced voltage in the accelerating

FIGURE 3

l_h vs f , for $\tau_q = 100$ hrs

$$l_b \sim \text{Const.} \left(\frac{\alpha R}{2 + \alpha \frac{R}{\rho}} \right)^{\frac{1}{2}} \cdot K_s \cdot \frac{1}{E^{\frac{1}{2}}} \cdot \frac{1}{f}$$

structure (again lower q value desired); ν_s , the synchrotron oscillation wave number and in terms of ion trapping in the potential well of the circulating electron beam. Here, only the latter two aspects will be further mentioned. The synchrotron oscillation wave number, for a "non-distorted bucket", is given by

$$\nu_s = (f_s/f) = [(f_s/f_o)(\alpha_p V \cos \phi_s/2\pi E)]^{1/2}, \text{ which}$$

can be written as

$$\nu_s = [C_Y/4\pi^2 ec]^{1/2} \cdot [I_1 I_2]^{1/2} \cdot F_{rf}^{-1} \cdot E^{3/2}.$$

Assuming again a fixed quantum lifetime, τ_q , value, and using the above given $q = F(f)$ relationship, it follows that:

$$\nu_s \sim \text{Const. } \rho^{-1/2} (\alpha_p R) E f$$

In general, it is desirable to avoid high ν_s values, because of potential betatron-synchrotron resonances, i.e. sidebands of the principal lattice resonances given by $\nu_\beta - n\nu_s = m$ (low n values, unfavorable). With accelerating frequency values of $f \sim 500$ MHz, ν_s values of $\sim 0.1-0.01$ will be encountered, resulting in greater constraints on the choice of permissible ν_x, ν_y , the betatron oscillation frequency, values. With a choice of $f = 50$ MHz, ν_s values of less than 0.01 are readily present, avoiding thereby the problem of lossy resonant sidebands.

As a result of residual gas ionization with resultant ion acceleration towards the electron beam, ion trapping in a transverse oscillatory motion can occur. This causes partial neutralization of the electron beam space charge and results in a tune shift ($\Delta\nu_{x,y}$) of the transverse oscillatory motion. In general, tune shifts greater than 0.25 ν units are considered harmful because of crossing into and through structure resonant stopbands. The standard remedy for this problem is the use of electrostatic clearing fields which accelerate the ions into the

vacuum chamber wall. A very serious drawback of this procedure in high intensity storage rings is the increase of the vacuum envelope wall impedance with the introduction of the clearing electrodes, aggravating thereby the potential for instability thresholds at lower beam current values.

The mechanism of ion trapping has been treated quantitatively by Kohaupt.⁶ Depending on the magnitude of the electron beam intensity, the ions are accelerated towards the potential well of the electron beam and either trapped into a transverse oscillatory motion around (through) the electron beam or gain sufficient transverse energy to traverse through the potential well to be lost on the vacuum chamber envelope. Stable transverse oscillatory motion of the ions occurs if

$$I_{e-} < I_{st} \text{ with } \text{---}$$

$$I_{st} = 3 \cdot 10^7 A \sigma_x \sigma_y l_{bb}^{-2} (1 + \sigma_y / \sigma_x) \quad \text{where}$$

A is the ion mass number and l_{bb} the bunch separation distance, i.e. for $I_{e-} > I_{st}$ the ions are accelerated into the wall and no partial beam neutralization occurs. Since $l_{bb} = C/f$ (for a system where all available rf "buckets" are filled), lower I_{st} values are encountered with the choice of a lower accelerating frequency. If I_{st} is sufficiently low, clearing electrodes will not be needed, since the stable (for ion trapping) current value will readily be traversed during the injection process. (If need be, empty "buckets" could be used, to increase l_{bb} temporarily during the injection process.) To illustrate this, some typical values are given here for the NSLS storage ring, as follows: $f = 50$ MHz, $l_{bb} = 5$ m, $I_{st} \simeq 0.1$ A for H_2 , $I_{st} \simeq 1.5$ A for CO. With design parameters for this ring of 0.5 A, 2.5 GeV or 1.0 A, 2.0 GeV the stable current value (I_{st}) is readily exceeded, taking into account the presence of lighter ion species only. No clearing electrodes are incorporated in this ring, suggesting, however, the need for special precautions to prevent contamination from heavier ion species (hydrocarbons). If, instead a high

frequency accelerating system would be adopted here, the following values would be encountered: $f = 500$ MHz, $l_{bb} = 0.5$ m, $I_{st} \approx 10$ A for H_2 ; $I_{st} \approx 150$ A for CO, indicating the impossibility of exceeding the ion trapping stable current. Consequently, in this case clearing electrodes would be required in the ring structure.

Other aspects entering into the choice of accelerating system parameters are the certain presence of specific longitudinal and transverse beam instabilities. This will not be addressed here, other than to state that in general with the use of low frequency accelerating systems, current limitations are encountered associated with single bunch instabilities due to the self interaction of the electron bunch with its short range wake fields induced in the beam envelope. Alternatively, in case of high frequency accelerating systems, with its small bunch separation, current limitations are more likely to be encountered because of difficult to control multiple bunch instabilities associated with bunch to bunch long range wake field interactions.

Special Lattice Structure Sections

In order to extend the wavelength region available from a synchrotron radiation source or increase its photon flux available in a specific narrow wavelength region, special components have been developed such as the superconducting "wiggler" and the "undulator". Both devices are orbit perturbators with no net electron orbit deflection. Recalling that $\epsilon_c \propto \gamma^3/\rho$ and $P_{rf} \propto \gamma^4/\rho$, a high field wiggler provides for an economical way of extending the available photon spectrum to higher energy values. Assuming the use of 6T peak field values, a factor of approximately 5 (or more) in critical energy may be obtained. Therefore, state of the art dedicated synchrotron radiation sources will have an adequate number of long straight sections in the magnet lattice structure for hard wavelength wiggler sources. The objective of optimum source brightness leads to the criteria that β_x, β_y are small in magnitude in the center of the wiggler straight section

and also that the local dispersion function, η , is preferably equal to zero since $B \propto (\sigma_x \sigma_y)^{-1}$ where $\sigma_y = (\beta_y \epsilon_y)^{1/2}$ and $\sigma_x^2 = (\beta_x \epsilon_x + \eta^2 \sigma_\epsilon^2 / E^2)$. A more significant aspect of the objective to design for zero dispersion in the wiggler straight section is the desire to avoid antidamping and enlargement of the beam emittance. The magnitude of this has been calculated for a typical structure (NSLS, X-ray). By straightforward circumferential integration of the dispersion invariant in the lattice with and without wigglers it is found that⁷

$$(\epsilon_{x,w} / \epsilon_{x,o}) = \frac{1 + n_w \ell_w r_\rho^3 \bar{\mathcal{H}}_w / 2\pi \rho_o \bar{\mathcal{H}}_o}{1 + n_w \ell_w r_\rho^2 / 2\pi \rho_o} \quad \text{with} \quad r_\rho = \frac{\rho_o}{\rho_w}$$

$\bar{\mathcal{H}}_o$ is the average value of $\mathcal{H}$ in the structure without wiggler magnets and $\bar{\mathcal{H}}_w$ is the average value of $\mathcal{H}$ over the wiggler domain only. Further, the mean value of the dispersion invariant in a single period of the wiggler structure is given by⁸ $\bar{\mathcal{H}} \simeq \mathcal{H}_{in} + \beta_x \theta / 3$ where θ is the orbit arc extend per one quarter wiggler period. Inserting five wigglers with the following parameters, $\ell_w = 3\lambda_w$, $\lambda_w = 0.14$ m, $B = 5$ T, $\rho_w = 1.6$ m, $\theta = 16.7$ mrad, $\rho_o = 6.8$ m, in a straight section of $\bar{\beta} \simeq 1$ m and non-zero dispersion with $\bar{\mathcal{H}}_w \simeq \bar{\mathcal{H}}_o \simeq 0.06$ m, an emittance growth $(\epsilon_{w,x} / \epsilon_{x,o}) \simeq 2.4$ results. Alternatively, if these wigglers would be inserted in zero dispersion straight sections, then $\bar{\mathcal{H}}_w = 9 \cdot 10^{-5}$ m, $\bar{\mathcal{H}}_o = 0.06$ m and the equilibrium emittance would be reduced as $(\epsilon_{x,w} / \epsilon_{x,o}) \simeq 0.6$.

An undulator⁹ is a structure consisting of many low field wigglers in sequence either in the form of a flat pole wiggler or helical wiggler. Its basic objective is the generation of high photon flux, quasi monochromatic peaks in the synchrotron radiation frequency distribution, given by (median plane):

$$\lambda_K = \lambda_w (2k\gamma^2)^{-1} (1 + K^2) \quad \text{with} \quad K = 0.1 B \lambda_w \quad (\text{kG, cm}) \quad \text{and} \quad k = 1, 3, 5 \dots$$

The total photon flux available from the undulator is proportional with n_w , the number of undulator periods, however, the central brightness is proportional with n_w^2 , or ¹⁰

$$\left. \frac{dP_v}{d\Omega} \right|_{\substack{k=1 \\ \theta=0}} = \frac{2n_w^2 e^2 \gamma^2 K^2}{C(1+K^2)^2}$$

As shown by Kincaid¹¹ this central brightness (and the spectral line width $(\Delta\lambda/\lambda) \simeq 1/n_w k$) can only be obtained if the structure functions in the undulator straight section satisfy the criterion that $\sigma_x, \simeq \sigma_y, \simeq 1/\gamma\sqrt{n_w}$. This requires, for a typical synchrotron radiation lattice structure (e.g. NSLS-700 MeV ring), that the local β values in the undulator straight section are modest in magnitude ($\simeq 10$ m) rather than low ($\beta \simeq 1$ m) for optimum undulator brightness value. Also in this case is it desirable to locate the undulator in a straight section with zero local dispersion value in order to obtain maximum source brightness.

The foregoing synchrotron radiation source optimization aspects have been taken into account in the design of the two electron storage rings comprising the National Synchrotron Light Source, of which the principal parameters are:

	<u>X-ray Source</u>	<u>VUV Source</u>
Current, energy (A, GeV)	0.5; 2.5	1.0; 0.7
Circumference (m)	170	51
λ_c (Å)	2.5 (0.5) _w	31.6
Emittance, ϵ_x (m-rad)	$8 \cdot 10^{-8}$	$9 \cdot 10^{-8}$
SR Power (kW)	300 (5 wigglers)	12
Source $4\sigma_x, 4\sigma_y$	0.5x1.5 (arc)	0.4x1.2
(mm ²)	0.1x0.9 (wiggler)	(arc)

A more complete presentation of the NSLS basic design and parameters is given elsewhere.¹²

REFERENCES

1. G. K. Green, "Spectra and Optics of Synchrotron Radiation", BNL Report 50522, (1976).
2. M. Sands, "The Physics of Electron Storage Rings", SLAC Report 121 (1970).
3. L. Blumberg, J. Bittner, J. Galayda, R. Heese, S. Krinsky, J. Schuchman, and A. van Steenbergen, "National Synchrotron Light Source VUV Storage Ring", IEEE Trans. Nucl. Sci. NS-26 (1979) 3842-4.
4. S. Krinsky, L. Blumberg, J. Bittner, J. Galayda, R. Heese, J. Schuchman, and A. van Steenbergen, "Design Status of the 2.5 GeV National Synchrotron Light Source X-ray Ring", IEEE Trans. Nucl. Sci. NS-26 (1979) 3806-8.
5. G. Saxon and T. E. Swain, "The Choice of Radiofrequency for the Daresbury Storage Ring", Report DLSRF-R6, Daresbury, U.K. (1975).
6. R. D. Kohaupt, "Ion Cleaning Mechanism in the Electron-Positron Storage Ring Doris", Report DESY HI-71/2 (1971).
7. J. M. Paterson, J. R. Rees, H. Wiedemann, "Control of Beam Size and Polarization Time in PEP", Report Spear-186, PEP-125, July 1975.
8. A. Hutton, Part. Accel. 7, No. 3 (1976) 163.
9. H. Motz, et al., J. Appl. Phys. 24 (1953) 826.
10. D. F. Alferov, et al., Sov. Phys. Tech. Phys. 18 (1974) 1336.
11. B. Kincaid, J. Appl. Phys. 48 (1977) 2684.
12. A. van Steenbergen, Proc. Nat'l. Conf. on Synchrotron Radiation Instrumentation, June 1979, Nucl. Instrum. Methods   (1980)   .