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NATIONAL SYNCHROTRON LIGHT SOURCE (NSLS):  
AN OPTIMIZED SOURCE FOR SYNCHROTRON RADIATION

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Synchrotron radiation has a number of special characteristics that make electron storage rings and synchrotrons powerful tools for research with photons. Applications in both basic research and technology are possible and there are exciting prospects for the future with the design and construction of electron storage rings dedicated to synchrotron radiation production. Synchrotron radiation has a continuous spectrum ranging from the infrared to X-ray wavelengths. It is both intense and strongly polarized in the plane of the electron orbit. The light is emitted in pulses that are typically  $1 \times 10^{-9}$  sec long and have repetition frequencies of the order of  $1 \times 10^6$  pulses per second. With the current designs, beam cross sections of  $1 \text{ mm}^2$  or less can be achieved and the photons are sharply collimated in a narrow cone about the tangent to the orbit of the emitting particle.

Since the first sustained research program with synchrotron light began in 1961 at the National Bureau of Standards utilizing a 180 MeV electron ring, all the research programs world wide have used machines that have been designed for other purposes, high energy physics in particular. Realizing that with an optimized electron storage ring the future research with synchrotron light could be even brighter, a number of countries have proposed and started construction of dedicated facilities in the 1970's. In the sections that follow some of the considerations for an optimal design of a storage ring will be outlined and the choices of parameters for the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory (BNL) will be presented. Also the policy for utilization of NSLS beam lines will be described for both the 0.7 GeV (VUV) storage ring and the 2.5 GeV (X-ray) storage ring.

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## Synchrotron Source Optimization

The considerations of source parameters and source optics for synchrotron radiation research were discussed in detail in the classic report by G. K. Green.<sup>1</sup> A more complete discussion of sources and the characteristics of synchrotron light can be found in Ref. 2. This section relies heavily on Ref. 3 which contains more pertinent information. The single most important parameter that describes the optical quality of the source is its brightness and minimum emittances are desirable in order to achieve the optimum source brightness. This can be done by the proper choice of the storage ring magnet lattice that has maximum radiation damping of the transverse betatron oscillations. This choice of lattice would not be the same as the optimal design for a  $e^+e^-$  colliding beam facility. The dipole fields can also be increased in the magnet lattice to increase the photon flux and the critical energy of the photon spectrum for a given electron energy.

Following Green,<sup>1</sup> the central brightness can be expressed as

$$B = N_K(0, \lambda) / 2\pi \sigma_x \sigma_y \quad (1)$$

$$\text{with } x = x' = y = y' = 0$$

where  $x, x', y, y'$  are components of the four dimensional phase space of the source.  $\sigma_x$  and  $\sigma_y$  are the transverse dimensions of the electron source.  $N_K(0, \lambda)$  is the intensity of photons per unit band pass (with the multiplier  $K$  and the wavelength  $\lambda$ ), solid angle and time. This expression is correct in the limit where the radiation opening angle,  $\sigma_r$ , is large compared to the angular variations in the electron beam trajectories  $\sigma_r > \sigma'_x, \sigma_r > \sigma'_y$  where

$$\sigma_r \approx \frac{0.565}{\gamma} \left( \frac{\lambda}{\lambda_c} \right)^{.425} \quad (2)$$

Here  $\gamma$  is the ratio of the electron's energy to its rest mass,  $\lambda$  is the wavelength of the photon and  $\lambda_c$  is the critical wavelength of the storage ring.

In general the NSLS designs are consistent with these restrictions. Noting that the transverse dimensions of the source are related to the vertical and horizontal emittances  $\sigma_y = \sqrt{\epsilon_y \beta_y}$  and  $\sigma_x = \sqrt{\epsilon_x \beta_x}$ , the maximum brightness is obtained for minimum emittances for a given amplitude functions  $\beta_y$  and  $\beta_x$ , respectively. The vertical emittances  $\epsilon_y$  is driven by a coupling of the radial and horizontal motion of the electrons. In practical storage ring designs this coupling can be held to typically 0.1 so that  $\epsilon_y \sim 10^{-2} \epsilon_x$ .

An approximate expression for  $\epsilon_x$  has been developed by van Steenbergen<sup>3</sup> following Sands<sup>4</sup>

$$\epsilon_x \approx C_q \gamma^2 [(\Phi H ds) / 2\pi \rho^2] \quad (3)$$

Here  $C_q$  is a constant and  $\rho$  is the radius of curvature of the electron orbit.  $H$  is a function of the local dispersion of the electron beam and the line integral is evaluated around the storage ring. Therefore, the quantity in brackets is only a function of the magnetic lattice and has been evaluated for a number of storage rings.<sup>3</sup> Minimizing this quantity (0.055 for the 2.5 GeV ring at NSLS vs. 0.28 for the Photon Factory, the Japanese synchrotron light source, also at 2.5 GeV) gives the highest source brightness. Recalling the expression for the local spatial source size, the amplitude function  $\beta$

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should be a minimum at the source locations. This has also been achieved at the NSLS.

With a given magnet lattice the other fundamental parameter of choice is the radio frequency of the accelerating system to replace the energy loss due to synchrotron radiation. In Ref. 3 a detailed discussion was given for the choice of low, typically 50 MHz, versus high, typically 300 MHz, operation. Basically, the low frequency system is better for high beam current, with less problems from ion collisions in the vacuum envelope. On the other hand, the higher frequency provides shorter pulses better suited to timing experiments but will perhaps give lower beam current. The NSLS has gone with the low frequency system trying to optimize the brightness but foregoing some capabilities for timing experiments.

The last point in source design are considerations for the inclusion of special structures, namely, wigglers and undulators. In the case of wigglers, which are used to produce a harder spectrum extending to higher energy regimes, the source is a superposition of intensities from separate poles of the magnet. Hence, maximum source brightness is achieved with minimum values of  $\beta_x$  and  $\beta_y$  at the location of the Wiggler magnets. Also a minimum value, preferably zero, for the local dispersion function  $\eta$  is desired to keep the  $\sigma_x$  value small since more correctly

$$\sigma_x^2 = (\beta_x \epsilon_x + \eta^2 \sigma_e^2 / E^2) . \quad (4)$$

Here  $\sigma_e$  is the standard deviation in electron energy about  $E$ , the mean electron energy. Also with  $\eta = 0$ , there is no adverse effect on the source emittance; in fact, the installation of wigglers in straight sections with zero dispersion at NSLS would reduce the source emittance by 0.6 (see Ref. 3).

For undulators<sup>5</sup> the requirements on  $\beta_x$  and  $\beta_y$  are different. The undulator is a many pole magnet that produces a coherent superposition of radiation from each "pole", giving rise to an extremely bright, quasi-monochromatic source of radiation. For the functioning of these devices  $\beta_x$  and  $\beta_y$  must be modest so that  $\sigma'_x$  and  $\sigma'_y$  of the electron orbit are small.<sup>6</sup> This capability has been built into the 0.7 GeV storage ring at NSLS.

#### Experimental Utilization and Beam Lines at NSLS

In order to best match experimental equipment to the synchrotron source taking into account the above considerations two storage rings are in construction at the NSLS. Their principal design parameters are given in Table I.

The typical photon spectra from these rings are shown in Figure 1. Also shown in Figure 1 is the spectrum for a wiggler magnet, 6 Tesla field, to provide radiation at shorter wavelengths. Note the critical wavelength, the half power point in the spectrum, is reduced from the arc source value, 2.5 Å, to 0.5 Å resulting from the increase from 1.2T to 6T field.

A plan view of the NSLS facility is shown in Figure 2. As can be seen from this Figure there are possibilities for 16 beam ports on the 0.7 GeV storage ring and 28 beam ports on the 2.5 GeV storage ring. All of these beam lines will ultimately be instrumented in one of two ways, either by the NSLS as a facility line open to the general public or by a participating research team (PRT) which provides up to 100% of the funding in exchange for a maximum of three-fourths usage. The remaining quarter

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Table I. Design Parameters for the X-ray and VUV Storage Rings at NSLS

	X-ray Source	VUV Source
Current, energy (A, GeV)	0.5; 2.5	1.0; 0.7
Circumference (m)	170	51
$\lambda_c$ (Å)	2.5 (arc) 0.5 (wiggler)	31.6 (arc)
Emittance, $\epsilon_x$ (m-rad)	$8 \times 10^{-8}$	$9 \times 10^{-8}$
SR Power (kW)	300 (5 wigglers)	12
Source $4\sigma_x, 4\sigma_y$ (mm <sup>2</sup> )	$0.5 \times 1.5$ (arc) $0.1 \times 0.9$ (wiggler)	$0.4 \times 1.2$ (arc)

SYNCHROTRON RADIATION SPECTRA FOR THE NSLS DESIGN PARAMETERS

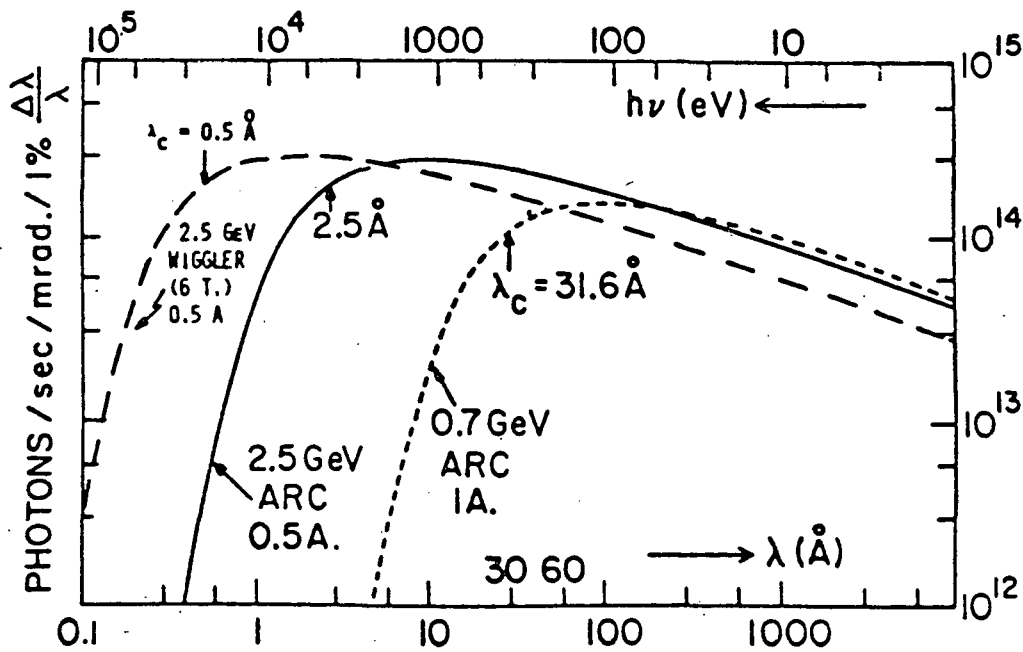


Fig. 1 Photon Spectra for NSLS. Plotted is log intensity per sec per mrad. per 1% band pass vs. log wavelength.

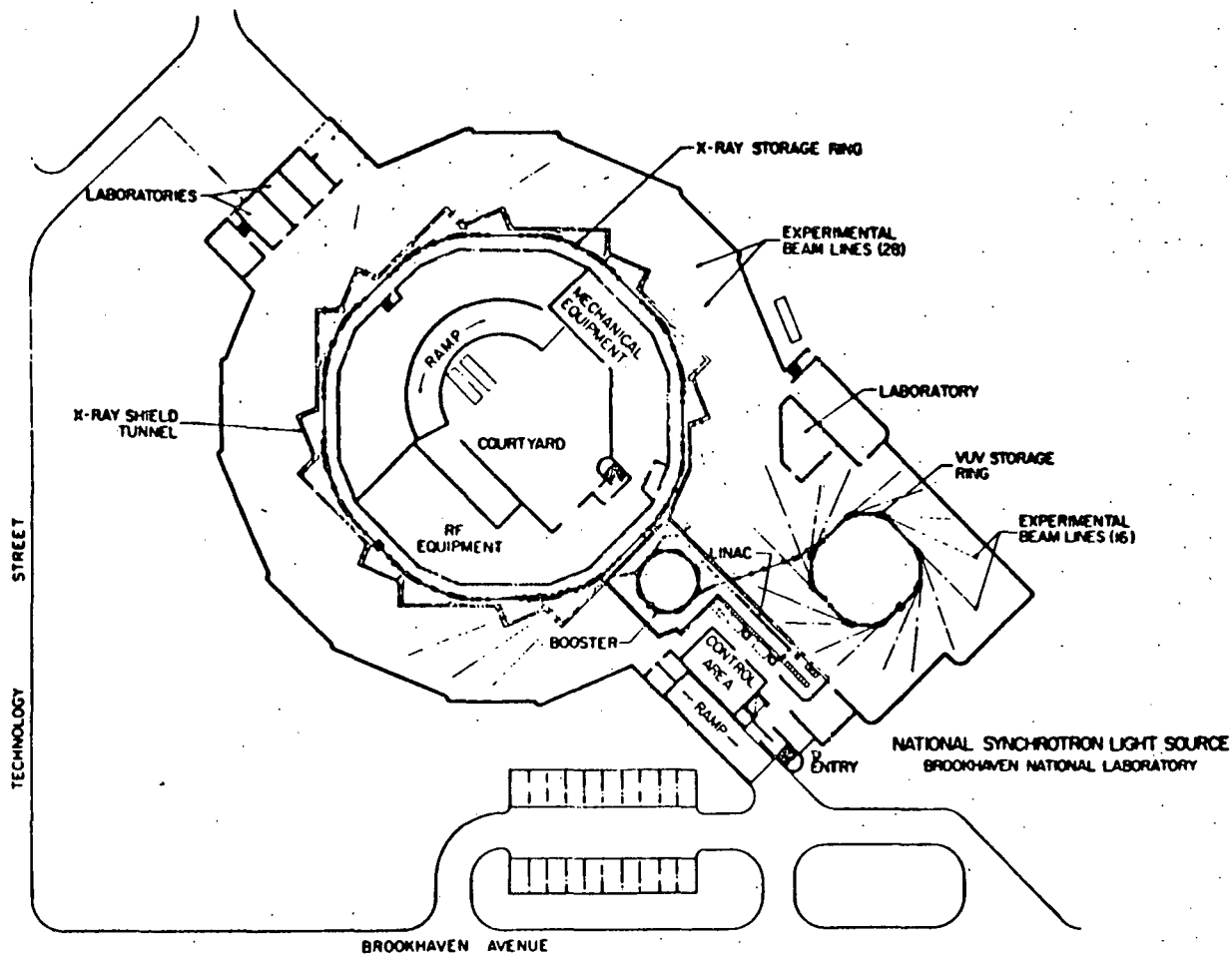


Fig. 2 Planned view of the NSLS facilities.

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time utilization will be available to outside users with cooperation from the PRT. Thus the details of the experimental equipment that will be available to the general user is diverse and in many cases are still in the planning stage. Tables II and III comprise lists of most of the proposed experimental capabilities for the VUV (0.7 GeV) and X-ray (2.5 GeV) storage rings, respectively. Some of these lines are being constructed by PRT's and others, marked with asterisks, in whole or in part by the NSLS. It should also be mentioned that for some experiments, they may be several beam lines available. More details of the facility beam lines are contained in Refs. 7 and 8 for the VUV and X-ray storage rings, respectively.

Table II. Proposed VUV Beam Lines

- \* HIGH RES. ARPES,<sup>a</sup> XPS<sup>b</sup> (35-1800 Å)
- \* MEDIUM RES. ARPES, XPS, SEXAFS<sup>c</sup> (8-1200 Å)
- \* SPECTROSCOPY — PHOTOCHEMISTRY
- \* DYNAMICAL SPECTROSCOPY
- \* BIOPHYSICAL SPECTROSCOPY
- IR SPECTROSCOPY
- ARPES, XPS
- \* TEST LINE
- \* FREE ELECTRON LASER
- \* Constructed in whole or in part by NSLS.

<sup>a</sup>ARPES: Angle-Resolved Photoelectron Spectroscopy

<sup>b</sup>XPS: X-Ray Photoelectron Spectroscopy

<sup>c</sup>SEXAFS: Surface Extended X-ray Absorption Fine Structure.

Table III. Proposed X-Ray Beam Lines

- \* SMALL ANGLE SCATTERING
- \* EXAFS,<sup>a</sup> SEXAFS,<sup>b</sup> XPS<sup>c</sup>
- \* X-RAY SCATTERING
- \* TOPOGRAPHY
- \* POWDER DIFFRACTION
- HIGH RESOLUTION SCATTERING
- DIFFUSE SCATTERING
- FLUORESCENCE ANALYSIS
- ATOMIC PHYSICS
- \* WIGGLER
- \* TEST LINE
- \* Constructed in whole or in part by NSLS.

<sup>a</sup>EXAFS: Extended X-Ray Absorption Fine Structure

<sup>b</sup>SEXAFS: Surface EXAFS

<sup>c</sup>XPS: X-ray Photo Electron Spectroscopy

In summary, the NSLS is constructing two optimized storage rings, one operating at 0.7 GeV with a critical wavelength of 31.6 Å and the other at 2.5 GeV with a critical wavelength of 2.5 Å. Both of these storage rings will be instrumented by a combination of NSLS facility beam lines and beam lines provided by participating research teams.

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