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The National Synchrotron Light Source*

by

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Abstract

The National Synchrotron Light Source comprises two high intensity electron storage rings for the generation of intense fluxes of synchrotron radiation in the VUV wavelength domain (700 MeV e^- ring) and in the X-ray wavelength domain (2.5 GeV e^- ring). A description is presented of the basic facility and the characteristics of the synchrotron radiation sources. The present plans for specific beam lines will be enumerated and the planned use of beam wigglers and undulators will be discussed.

Introduction and Description of the NSLS

Construction, at Brookhaven National Laboratory, of two high intensity electron storage rings for the purpose of providing for a large number of intense synchrotron radiation sources, was started in the fall of 1977. These sources are constructed to meet the rapidly growing interest of applying synchrotron radiation and its unique properties, such as high photon flux, wavelength tunability, natural collimation, specific polarization, time structure and small source size (high source brightness) to such diverse fields as the material sciences, atomic and molecular physics, biology and microelectronics technology. Completion of construction is expected by the fall of 1981 with the turn over of both storage rings for experimental utilization.

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The NSLS complex, consisting of a 100 MeV Linear Accelerator, a 100-700 MeV Booster Synchrotron, a 700 MeV, 1 Ampere, e^- storage ring for the VUV domain, a 2.5 GeV, 0.5 Ampere, e^- storage ring for the hard X-ray domain, and a large number of monochromatized photon lines, is shown in Fig. 1. The basic parameters of the two storage rings are given in Table I and a basic element (superperiod) of each storage ring is shown in Fig. 2. With the use of high beam bunch densities, as encountered in both storage rings, it is expected that the source brightness lifetime will be limited by the so-called Touschek effect, a loss of particles from longitudinal phase stability due to intrabunch electron scattering. For the design parameters, for the VUV ring, this lifetime value will be $\gtrsim$ 4 hrs, for the X-ray ring, at full energy, it is calculated to be in excess of 8 hrs.

Source Parameters

Since these synchrotron radiation sources are designed for diversified research, the characteristics of the circulating electron beam are important as they relate to the properties of the emitted synchrotron radiation. In general, a small beam emittance will permit higher photon source brightness values. This is particularly desired for experiments requiring small angular spread on a small sample, such as for protein crystallography. For specific experiments, such as for EXAFS and Topography, it may be more favorable, typically in terms of source stability, to sacrifice source brightness in favor of highest possible photon flux. Consequently, efforts have been made to design storage ring structures with more than a single beam optics solution. Here, however, only the source parameters associated with the "optics" solution are presented, as given in Table II. In this table the calculated photon flux magnitude at a few specific wavelength values are listed, a more complete "spectrum" of flux versus wavelength, also with a 6 Tesla orbit wiggler, is given in Fig. 3 together with a summary of the

NSLS experimental parameters, indicating also the details of the time structure of the synchrotron radiation sources.

Related to the unique properties of synchrotron radiation, a comparison with conventional photon sources is best made in terms of inherent photon source brightness (Ph/sec/eV/mrad^2/cm^2). This is detailed in Table III indicating not only that, typically, in the X-ray domain of the wavelength region improvements of 10^4 to 10^7 are anticipated, but also that, typically, in the VUV domain strong photon sources are now becoming available where essentially none existed before.

The VUV ring will have eight 75 mrad parts and eight 90 mrad ports. The X-ray ring will make use of 50 mrad ports (2 per magnet) of which each will normally be split in two (or more) branches, subtending typically 10 mrad (or less) per branch.

Planned Facility Beam Lines

As part of the NSLS construction phase, four instrumented photon lines will be built for the X-ray storage ring and four lines will be constructed for the VUV ring. These will be optimized for specific research objectives such as small angle scattering studies of biological structures, extended X-ray absorption fine structure studies (EXAFS), X-ray diffraction, etc.; and angle resolved photoelectron spectroscopy of solids, gas phase spectroscopy, fluorescent lifetime studies, etc. The plans for these eight beam lines, as listed in Table IV, are well advanced and detailed design of the instrumentation of a number of these lines has been started.

In order to facilitate more users than can be accommodated with the initial eight planned monochromatized photon lines, a policy of experimental utilization has been developed for the NSLS, whereby in addition to those beam lines constructed by the NSLS staff for general usage, a number of beam lines would be designed and instrumented by "Participating Research Teams" (PRT's) which, in return, would be given priority for a fraction of scheduled beam time for a specific period of time. In response to a solicitation of interest for future utilization of the NSLS, a substantial number of PRT's are now in formation and are expected to enhance significantly the early experimental utilization of the NSLS.

Wigglers and Undulators

A "wiggler" is a structure of several short sections of alternating polarity magnetic field which, in its totality, does not result in a net orbit deflection of the electrons and is intended to provide sources of lower critical wavelength magnitude. Recalling that $\varepsilon_c \propto E^2B$ and $P_{rf} \propto E^3B$ and that the cost of rf power is high, it is by now generally recognized that wigglers are the poor man's way to higher excitation. Assuming the use of 6T fields for the wiggler, a factor of ∿5, typically, in the critical energy, can be obtained. The use of a wiggler in a low β insertion can provide for a shorter wavelength source of very high brightness.

It is relevant for a synchrotron radiation source that the high field wiggler be located in a straight section of zero momentum dispersion in order to avoid antidamping and enlargement of the horizontal beam emittance, ε_x. Here the difference between a specifically optimized synchrotron radiation structure and a e^+e^- storage ring structure, parasitically used for synchrotron radiation research, is relevant. In colliding beam facilities the objective is to enhance e^+e^- luminosity which turns out to be directly proportional to ε_x. With the incorporation of a wiggler in the structure, in order to increase ε_c, the desire is to locate it in a high momentum dispersion straight section in order to increase the horizontal emittance and thereby the e^+e^- luminosity. The opposite is valid for a dedicated facility where the wiggler would always be located in a zero (or near zero) dispersion straight section in order to reduce the emittance. An example has been calculated whereby the use of 5 high field wigglers in the NSLS 2.5 GeV structure has been assumed. This is given in Table V indicating a significant difference in achievable emittances depending on the location of the wigglers in the storage ring lattice.

An undulator[2-6] is a structure consisting of many low field wigglers in sequence, either in the form of a flat pole wiggler or helical wiggler. The basic relationships are given in Table VI. Its great attraction is the on axis brightness proportionality with n_w^2, where n_w is the number of undulator periods, making possible two to three orders of magnitude enhancement with a reasonable structure. Typically, for the NSLS VUV storage ring (700 MeV) an undulator is planned for which a possible photon flux, at $\lambda = 400$ Å, of approximately $8\ 10^{16}$ ph/sec/1% $\Delta\lambda/\lambda$ has been calculated[7] using a $n_w = 50$ structure. Because the brightness enhancement is dependent on the $\sigma_{y'}, \sigma_{x'}$ values in the structure straight sections, more modest (rather than low) β values are required in the lattice insertions for optimum brightness enhancement.

A significant drawback of the helical wiggler is the enhanced horizontal-vertical coupling of the x-y motion, resulting in significantly increased vertical emittances, i.e. the turn on of the photon source for the user of the undulator line would seriously affect other experiments using the arc sources in the structure. An attractive feature of the flat pole wiggler is the possibility of orienting it vertically, providing for a rotated plane of polarization compared with the arc sources. This permits a more favorable arrangement of specific experimental equipment (diffractometer table horizontal).

On completion of the NSLS construction phase it is planned to have ready for commissioning two superconducting wigglers for the X-ray ring. At a later stage it is planned to construct a multipole coherent wiggler (undulator) for the VUV ring.

References

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Figure Captions

Fig. 1 National Synchrotron Light Source, Brookhaven National Laboratory, Plan View.

Fig. 2 Superperiods of the X-ray and VUV storage rings.

Fig. 3 Synchrotron radiation spectra for the NSLS design parameters; NSLS, summary experimental parameters, X-ray, VUV.

TABLE I

X-RAY STORAGE RING PARAMETERS

ENERGY RANGE	2.5 GeV - 0.7 GeV
DESIGN CURRENT	1 A (2 GeV) ($3.9\ 10^{12}\ e^-$)
	0.5 A (2.5 GeV) ($1.9\ 10^{12}\ e^-$)
RADIATED POWER (0.5 A, 2.5 GeV)	$252 + 9N_W$ (kW)
λ_c (ϵ_c) AT 1.22 T (B)	2.48 Å (5 keV)
6.0 T (W)	0.5 Å (25.0 keV)
$\tau_{Touschek}$ (0.7 GeV, 1 A)	$\gtrsim$ 0.6 hrs ($\hat{V}_{RF} \simeq 800$ kV)
(2.5 GeV, 0.5 A)	$\gtrsim$ 8 hrs (same)
$\hat{B}$ (ρ)	1.22 T (6.875 m)
CIRCUMFERENCE	170.08 m
τ_{orb} (h)	567.7 nsec (30)
DAMPING TIMES (0.7 GeV)	$\tau_x \simeq \tau_y \simeq 256$ msec; $\tau_\epsilon \simeq 129$ msec.
(2.5 GeV)	$\tau_x \simeq \tau_y \simeq 5.6$ msec; $\tau_\epsilon \simeq 2.8$ msec.
LATTICE STRUCTURE	SEPARATED FUNCTION, TRIPLETS
NUMBER OF SUPERPERIODS	8
LONG STRAIGHTS	4.50 m
MAGNET COMPLEMENT	16 B (2.7 m)
	40 Q (0.45 m)
	16 Q (0.80 m)
	32 S (0.20 m)

VUV STORAGE RING PARAMETERS

ENERGY	0.7 GeV
DESIGN CURRENT	1 A ($1.2\ 10^{12}\ e^-$)
RADIATED POWER (1 A)	11.3 kW
λ_c (ϵ_c)	31.6 Å (390 eV)
$\tau_{Touschek}$	$\gtrsim$ 4 hrs ($\hat{V}_{RF} \simeq 200$ kV)
B (ρ)	1.2 T (1.91 m)
CIRCUMFERENCE	51.02 m
τ_{orb} (h)	170.2 nsec (9)
DAMPING TIMES	$\tau_x \simeq \tau_y \simeq 21$ msec; $\tau_\epsilon \simeq 11$ msec
LATTICE STRUCTURE	SEPARATED FUNCTIONS, DOUBLETS
NUMBER OF SUPERPERIODS	4
LONG STRAIGHTS	3.26 m
MAGNET COMPLEMENT	8 B (1.5 m)
	24 Q (0.3 m)
	12 S (0.20 m)

TABLE II

EXPERIMENTAL PARAMETERS, X-RAY RING

"OPTICS" SOLUTION, E = 2.5 GeV, 10% COUPLING

$\epsilon_X = 8.1\ 10^{-8}$ RAD M; $\epsilon_Y = 8.1\ 10^{-10}$ RAD M; $\sigma_\epsilon(\Delta p/p) = 8.2\ 10^{-4}$

SOURCES	$2\ \sigma_{X,T}$(MM)	$2\ \sigma_Y$(MM)	$N_\gamma(\lambda)$ (PH/S/MRAD/0.5 A/1% $\Delta\lambda/\lambda$)
XW1	0.65	0.035	
WIGGLER SOURCES; $\lambda_c = 0.5$ Å $\hat{B} = 6$T; $\epsilon_c = 25$ keV			$2\ 10^{14}$ AT $\lambda = 1$ Å (12.3 keV) $4\ 10^{13}$ $\lambda = 0.2$ Å (62 keV) $3\ 10^{12}$ $\lambda = 0.1$ Å (123 keV)
B(2.5°)	0.9	0.25	
B(10°) B(32.5°)	0.5	0.2	
B(2.5°)	0.7	0.2	
ARC SOURCES: $\lambda_c = 2.5$ Å $\hat{B} = 1.2$ T; $\epsilon_c = 5$ keV			$2.5\ 10^{14}$ AT $\lambda = 10$ Å $3.2\ 10^{13}$ $\lambda = 1$ Å $6.0\ 10^{13}$ $\lambda = 4000$ Å

EXPERIMENTAL PARAMETERS, VUV RING

"OPTICS" SOLUTION, E = 0.7 GeV, 10% COUPLING

$\epsilon_X = 8.7\times10^{-8}$ RAD.M; $\epsilon_Y = 8.8\times10^{-10}$ RAD.M; $\sigma_\epsilon(\Delta p/p) = 4.4\times10^{-4}$

SOURCES	$2\sigma_{X,T}$(MM)	$2\sigma_Y$(MM)	$N_\gamma(\lambda)$ (PH./S/MRAD/1A/1% $\Delta\lambda/\lambda$)
B (5°)	0.8	0.2	
B(22°) B(67°)	0.65	0.2	
B(50°)	0.55	0.2	
ARC SOURCES; $\lambda_c = 31$ Å $\hat{B} = 1.2$ T; $\epsilon_c = 0.4$ keV			1.9×10^{13} AT $\lambda = 10$ Å 1.5×10^{14} AT $\lambda = 100$ Å 6.5×10^{13} AT $\lambda = 4000$ Å
UCW			$N_\gamma(\lambda)$(PH./S/1A/1% $\Delta\lambda/\lambda$)
	2.0 ($2\sigma_{X'} = 0.15$ MR.)	0.15 ($2\sigma_{Y'} = 0.025$ MR.)	
UNDULATORS; $B_0 = 0.4$ T, $\lambda_W = 5$ CM N = 50; $g = 3$ CM, K = 2			k=1; $8\ 10^{16}$ AT $\lambda = 400$ Å k=3; $6\ 10^{16}$ $\lambda = 133$ Å

TABLE III

COMPARISON RADIATION SOURCES

→ Å

	0.1 — 1 — 10	100	1000		10000
	(Hard) X-Ray (Soft)	VUV	UV	Vis	Infrared
OTHER SOURCES	Bremsstrahlung Continuum Characteristic Emission	(Some Line Sources)	Gas Discharge		Lasers
NSLS	Wiggler (5T) Arc Elem. (1.2T) 2.5 GeV Ring	Arc Elements 0.7 GeV Ring			
Brightness* Synch. Rad. / Other	10^7 x Bremss. Cont. 10^4 x Char. Emiss.		Typ. 10^2x He (800 Å)		$\approx 10^{-10}$

Multipole Coherent Wiggler (N = 100)

Narrow Band Emiss. 10^8 x Char. Emiss.

EXAMPLE: X-ray Ring, 2.5 GeV, 0.5 A, Arc Source, at λ = 10 Å

$B \cong 5\ 10^{15}$ ph s^{-1} $(eV)^{-1}$ $(mrad)^{-2}$ $(cm)^{-2}$

TABLE IV

PLANNED FACILITY BEAM LINES

VUV BEAM LINES

U1A:	HIGH RESOL. ARPES, XPS	35 - 1200 Å
U1B:	MED. RESOL. ARPES, XPS, SEXAFS	8 - 1200 Å
U2:	HIGH RESOL. GAS PHASE SPECTROSCOPY	300 - 3000 Å
U3:	MED. RESOL. SPECTROSCOPY PHOTOCHEMISTRY, CROSSED MOLECULAR BEAMS	300 - 1000 Å
U4:	FLUORESCENT LIFE TIME	> 1200 Å
(	LITHOGRAPHY, X-RAY MICROGRAPHY	10 - 200 Å)

X-RAY BEAM LINES

X1A:	SMALL ANGLE SCATTERING, BIOLOGY	0.7 - 5 Å
X1B:	SMALL ANGLE SCATTERING, MATERIALS	0.7 - 5 Å
X2:	EXAFS, SEXAFS, XPS	0.5 - 25 Å
X3:	X-RAY DIFFRACTION	0.4 - 4 Å
X4:	TOPOGRAPHY, DISP. POWDER DIFFRACTION	WHITE BEAM

WIGGLER PORT; $\lambda_c = 0.6$ Å, $\lambda \gtrsim 0.1$ Å ($\lesssim$ 100 keV)

TABLE V

LOCATION OF WIGGLERS IN THE STRUCTURE

PARASITIC SYNCHROTRON RADIATION SOURCE e^+-e^- COLLIDING BEAMS	DEDICATED SYNCHROTRON RADIATION SOURCE
OBJECTIVE: ENLARGEMENT ϵ_X, (INCREASE ϵ_{CRIT})	INCREASE ϵ_{CRIT}, (DECREASE ϵ_X)

RECALL $L_{e^+e^-} \simeq \dfrac{\pi f(\Delta\nu)^2 k_b \gamma^2 \epsilon_x}{r_e \beta_{o,y}}$

WIGGLER EFFECT ON ϵ_X: $(\epsilon_{X,W}/\epsilon_{X,0}) = \dfrac{1+n_W \ell_W r_\rho^3 \overline{\mathcal{H}}_W/2\pi\rho_0 \overline{\mathcal{H}}_0}{1+n_W \ell_W r_\rho^2/2\pi\rho_0}$ WITH $r_\rho = (\rho_0/\rho_W)$

$\mathcal{H} = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$, "INVARIANT". BEHAVIOR IN ^{1}

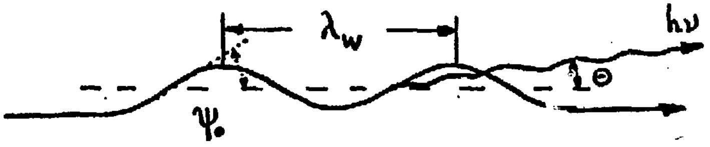
$\overline{\mathcal{H}} \simeq \mathcal{H}_{in} + \dfrac{\beta_X \theta}{3}$

ASSUME (NSLS 2.5): $n_W = 5$, $\ell_W = 3\lambda_W$, $\lambda_W = 0.14$ M, $\hat{B} = 5$ T., $\rho_W = 1.6$ M, $\theta = 16.7$ MRAD, $\rho_0 = 6.8$ M, $\beta_X \simeq 1$ M.

LOCATION: AVERAGE DISPERSION STRAIGHT	ZERO DISPERSION INSERTION
$\overline{\mathcal{H}}_W \simeq \overline{\mathcal{H}}_0 \simeq 0.06$ M.	$\overline{\mathcal{H}}_W = 9\ 10^{-5}$ M, $\overline{\mathcal{H}}_0 = 0.06$ M.
$\longrightarrow \epsilon_{X,W} \simeq 2.4\ \epsilon_{X0}$	$\longrightarrow \epsilon_{X,W} \simeq 0.6\ \epsilon_{X0}$
[SIMILARLY: $\sigma_{\epsilon,W} \simeq 1.5\ \sigma_{\epsilon,0}$	$\sigma_{\epsilon,W} \simeq 1.5\ \sigma_{\epsilon,0}$]

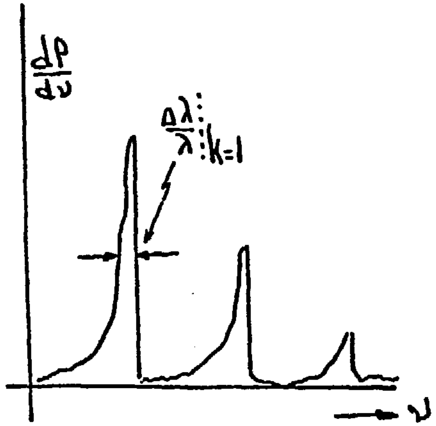
TABLE VI

UNDULATORS



APPROX. SINUSOIDALLY TRANSVERSE B FIELD: $B_n = B_0 \sin(2\pi z/\lambda_W)$; n_W PERIODS.

SPECTRUM: $\lambda_K = \frac{\lambda_W}{2k\gamma^2}(1 + K^2 + \gamma^2\theta^2)$; $k = 1,3,5,\ldots$; WITH $K = \gamma\psi_0 = \frac{e\, B_0 \lambda_W}{2\pi\, m_0 c^2}$



I.E. QUASI MONOCHROMATIC PEAKS IN THE FREQUENCY DISTRIBUTION.

FOR $\theta = 0$, LINE WIDTH $(\frac{\Delta\lambda}{\lambda})_k \simeq \frac{1}{nk}$; FOR FINITE θ, $(\frac{\Delta\lambda}{\lambda})_k \simeq \gamma^2\theta^2/(1 + K^2/2)$

MINIMUM $(\Delta\lambda/\lambda)$ DEMANDS $\sigma_{x'} \simeq \sigma_{y'} \simeq 1/\gamma\sqrt{n_W} \rightarrow$ INSERTION!

MAXIMUM SR POWER IN $k = 1$ MODE, FOR $K \simeq 1$, I.E. $B_0(T).\lambda_W(\text{CM}) = 1$

EXAMPLE: ACO SUPERCON. WIGGLER

$n_W = 23.5$; $\lambda_W = 4$ CM; $\bar{B}_0 = 0.25$ T; $\hat{B}_0 = 0.4$ T; $\lambda_{k=1} = 270$ Å

PHOTON FLUX: TOTAL FLUX $\propto n_W$, HOWEVER, CENTRAL BRIGHTNESS $\propto n_W^2$ AS

$$\frac{dP_\nu}{d\Omega}\bigg|_{\substack{k=1\\ \theta=0}} \frac{2\, n_W^2\, e^2\, \gamma^2\, K^2}{c\,(1+K^2)^2}$$

HELICAL WIGGLER
CIRCULARLY POLARIZED RADIATION
COUPLING $0.1 \rightarrow 1$, $\varepsilon_y \simeq \varepsilon_x$

FLAT POLE WIGGLER
PLANE POLARIZED RADIATION
ORIENTATION, PLANE OF POLARIZATION!
REDUCTION IN ε_x (OR ε_y), AT $\eta = 0$

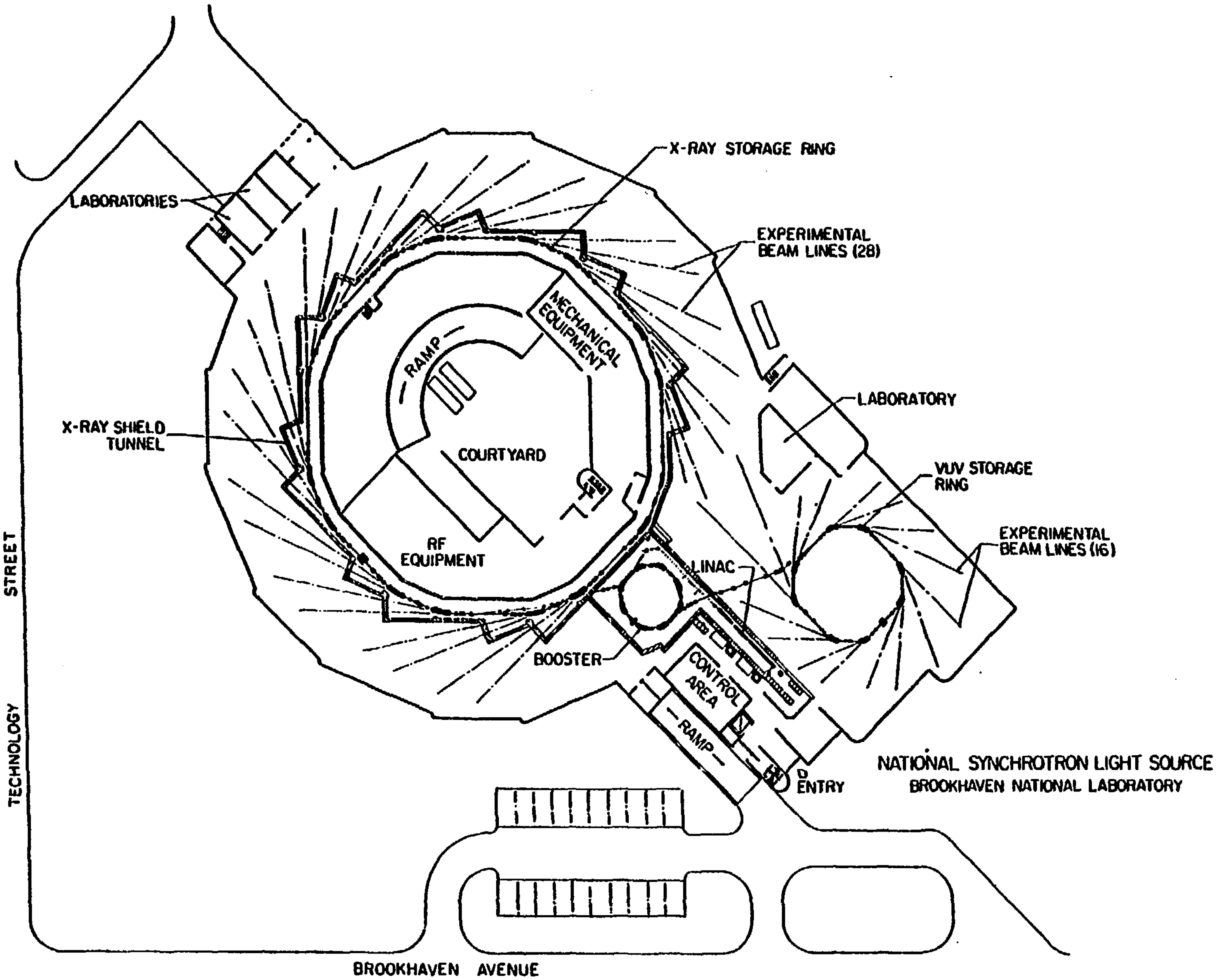

X-RAY STORAGE RING
LABORATORIES
EXPERIMENTAL BEAM LINES (28)
MECHANICAL EQUIPMENT
RAMP
LABORATORY
X-RAY SHIELD TUNNEL
COURTYARD
VUV STORAGE RING
EXPERIMENTAL BEAM LINES (16)
RF EQUIPMENT
LINAC
STREET
BOOSTER
CONTROL AREA
RAMP
ENTRY
NATIONAL SYNCHROTRON LIGHT SOURCE
BROOKHAVEN NATIONAL LABORATORY
TECHNOLOGY
BROOKHAVEN AVENUE

FIGURE 1

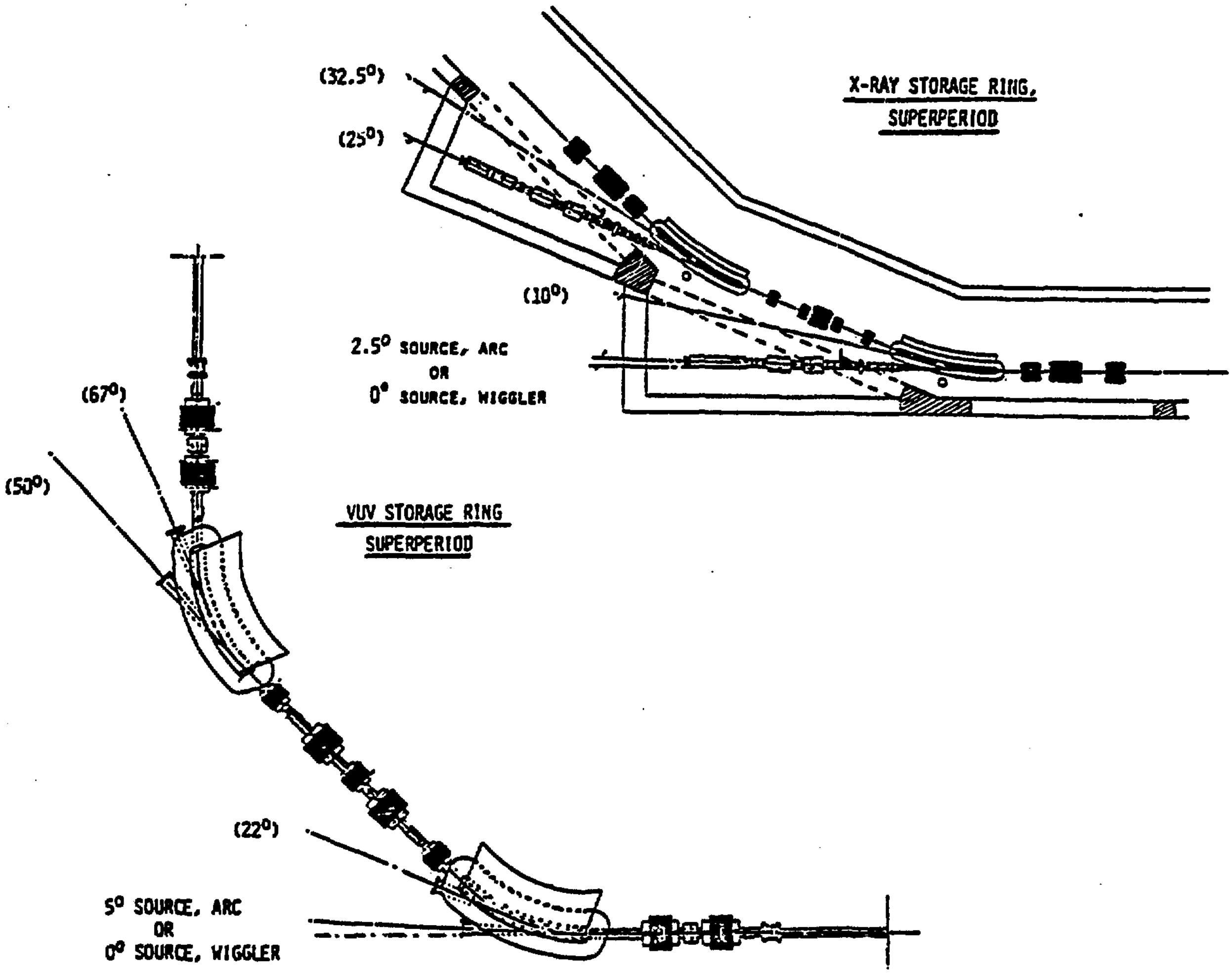

(32.5°)
(25°)
X-RAY STORAGE RING,
SUPERPERIOD
(10°)
2.5° SOURCE, ARC
OR
0° SOURCE, WIGGLER
(67°)
(50°)
VUV STORAGE RING
SUPERPERIOD
(22°)
5° SOURCE, ARC
OR
0° SOURCE, WIGGLER

FIGURE 2

SYNCHROTRON RADIATION SPECTRA FOR THE NSLS DESIGN PARAMETERS

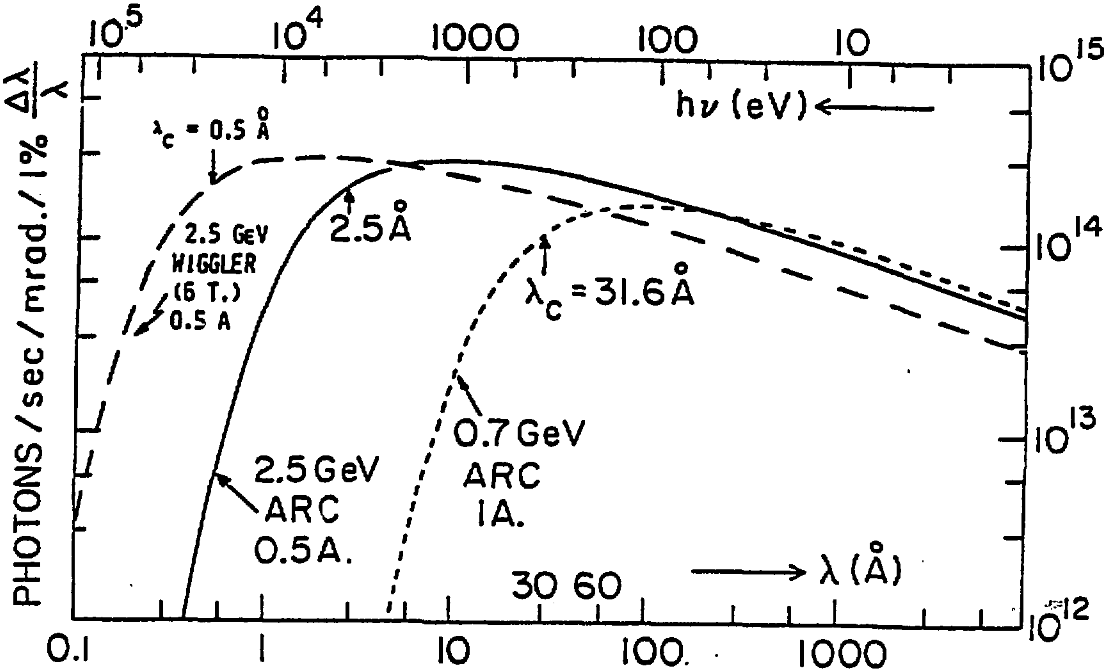


FIGURE 3

NSLS SUMMARY EXPERIMENTAL PARAMETERS, X-RAY, VUV

	X-RAY (WIGGLER)	X-RAY (ARC)	VUV (ARC)
WAVELENGTH (Å)	1	10	100
[λ_c(Å); ϵ_c(KEV)]	[0.5 ; 25.0]	[2.5 ; 5.0]	[31 ; 0.4]
SOURCE DIMENSIONS			
$2\sigma_Y \times 2\sigma_{X,T}$ (MM^2)	0.035 x 0.65	0.2 x 0.5	0.2 x 0.55
ARC LENGTH, $\Delta x'$ (MRAD)	5	10	60
VERT. OPENING ANGLE (MRAD) ($2\sigma'$)	0.3	0.4	1.4
FLUX, PER 0.1% $\Delta\lambda/\lambda$ (PH/SEC)	10^{14}	2.5 10^{14}	10^{15}
TIME STRUCTURE			
NUMBER OF BUNCHES	30	30	9
ORBITAL TIME (NSEC)	568	568	170
EFFECTIVE BUNCH LENGTH (NSEC)	1.5	1.7	1.1
BEAM PORTS, MAX.	$N(\hat{N} = 5)$	(28 - N)	16