DESIGN AND PROJECT STATUS OF THE NATIONAL SYNCHROTRON LIGHT SOURCE; STORAGE RINGS (2.5 GeV, 0.7 GeV) FOR THE GENERATION OF BRIGHT SYNCHROTRON RADIATION SOURCES*

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Abstract

Two high intensity storage rings are being constructed at Brookhaven National Laboratory for the generation of intense fluxes of synchrotron radiation in the VUV wavelength region (700 MeV ring, $\lambda_c = 31.5$ Å) and in the X-ray wavelength region (2.5 GeV ring, $\lambda_c = 2.5$ Å). A description is given of the facility, the main features of the storage rings are presented and the basic parameters are enumerated. High field superconducting wigglers, to lower the short wavelength cutoff in the X-ray ring, and undulators, for flux enhancement or a free electron laser experiment will be incorporated and parameters are given here. Special design aspects to optimize the electron storage rings as dedicated synchrotron radiation sources will be emphasized and the status of the project will be given.

MASTER

INTRODUCTION

Construction of two storage rings for a multiplicity of high brightness 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 materials sciences, atomic and molecular physics, biology and microelectronics technology.

SOURCE PARAMETERS

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 VUV ring will have eight 75 mrad ports 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) of orbit arc per branch. Source parameters for both the X-ray and VUV rings are summarized in Table 1. In this Table the calculated photon flux magnitude at a specific wavelength value is listed; a more complete "spectrum" of photon flux versus wavelength, also with a 6 Tesla orbit wiggler in the X-ray ring, is given in Fig. 2. By means of precision tunable monochromators and associated mirror systems, this synchrotron radiation continuum will be available as "line" sources (say $\Delta\lambda/\lambda = 10^{-4}$) in the wavelength region ranging from 0.1 Å to the visible region (5000 Å) and above.

Extreme source stability is required. Typically, for biology small angle scattering work, sample illumination areas as small as 50 μm in linear dimension will be used. A number of measures in the design of the NSLS have been taken to promote synchrotron radiation source stability, such as criteria for magnet excitation power supply stability ($<1/10^4$), component and experimental environmental temperature control ($\pm 1^\circ\text{C}$) and foundation

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FIG. 1. NATIONAL SYNCHROTRON LIGHT SOURCE stability (special interlocking of segmented foundation sections, short term foundation temperature stability, mass isolation of nearby vibrating components).

STORAGE RING STRUCTURES

Since both the VUV and X-ray storage rings are designed as dedicated synchrotron radiation sources, their structures are optimized for favorable photon source parameters. This resulted in magnet lattice structures with high magnetic field values, in order to obtain the highest photon energy at minimum rf power requirements. Similarly, higher source brightness is obtained with minimum horizontal emittance. This led in the early designs^{1]} to the use of achromatic bend sections in the NSLS lattice structures for which $\mathcal{H}$ is minimum, compared with alternate more conventional lattice structures^{2]} ($\mathcal{H}$ is the dispersion invariant, $\mathcal{H} = \eta^2 + 2\eta\eta' + \beta\eta'^2$, with $\eta(s)$ the electron orbit dispersion function), recalling that for a separated function structure^{3]} $\epsilon_x = C_q \gamma^2 [(\mathcal{H} ds)/2\pi]^2$. A favorable consequence of the use of achromatic bend sections is the zero magnitude of the momentum dispersion in the lattice long straight sections, where the rf cavities (reduction of synchrotron-betatron coupling) and wigglers (further reduction of transverse emittance^{4,5]} are located. A superperiod of the X-ray storage ring^{6]} is shown in Fig. 3. As shown, the achromatic structure is complemented with quadrupole triplet combinations providing for great flexibility in obtaining a variety of optical solutions. One example of this, the so-called "optics" solution is shown in Fig. 4 indicating the β function and η function behavior in the X-ray lattice. With the adoption of basic achromatic arc structures, the location of two sets of sextupoles to correct the lattice natural chromaticities ($\xi = \Delta v/(\Delta p/p_0)$) is limited to the straights adjacent to the focusing quadrupole in the middle of the superperiod and relative large sextupole components are required. With sextupole values to correct the chromaticities to $\xi_x = \xi_y = +3$, which should result in stability against head-tail oscillations^{7]} the momentum dependence of the betatron tunes and amplitude functions have been computed and found to be acceptable. In addition,

FIG. 2 SYNCHROTRON RADIATION SPECTRA FOR THE NSLS DESIGN PARAMETERS

TABLE 1
NSLS SUMMARY EXPERIMENTAL PARAMETERS, X-RAY, VUV

WAVELENGTH (Å)	X-RAY (WIGGLER)*	X-RAY (ARC)	VUV (ARC)
$(\lambda_c(\text{Å}), \lambda_e(\text{keV}))$	(0.5, 25.0)	(2.5, 5.0)	(31, 0.4)
SOURCE DIMENSIONS			
$2\sigma_x \times 2\sigma_y$ (mm)	0.04 x 1.0	0.2 x 0.5	0.2 x 0.55
ARC LENGTH, Δs (mrad)	5	10	60
VERT. OPENING ANGLE (mrad) (2σ)	0.3	0.4	1.4
FLUX, PER 0.15 μA (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)	0.4	0.4	0.3
BEAM PORTS, MAX.	$N(8) = 5$	$(28 - N)$	16

(NOTE: $\lambda_c(\text{Å}) = 100.4/B(\text{kG})^2(\text{GeV})$; $\lambda_e(\text{keV}) = 12.4/\lambda_c(\text{Å})$; SPECTRUM PEAK $\sim 1.5 \lambda_c$)
* 5 POLE, 6 TESLA SUPERCONDUCTING WIGGLER.

the limiting amplitude of stable betatron oscillations has been computed by means of particle tracking and found to be several times that contained within the lattice "stay-clear-aperture".

FIG. 4 2.5 GeV LATTICE STRUCTURE

TABLE 2

NSLS, ACCELERATOR AND STORAGE RING PARAMETERS

	X-RAY STORAGE RING	VUV STORAGE RING	BOOSTER SYNCHROTRON
ENERGY RANGE (GeV)	0.7-2.5	0.7	0.1-0.7
DESIGN CURRENT (A.)	0.5 (1.9 10 ¹² e ⁻)	1.0 (1.1 10 ¹² e ⁻)	0.02 (=10 ¹⁰ e ⁻)
CIRCUMFERENCE (m.)	170.1	51.0	28.35
B(max.), (ρ) (T.), (m.)	1.22 (6.875)	1.22 (1.91)	1.22 (1.91)
τ _{ORB} , (h) (NSEC)	567.7 (30)	170.2 (9)	94.6 (5)
DAMPING TIMES (SEC.)	τ _x =τ _y =0.006; τ _ε =0.003*	τ _x =τ _y =0.021; τ _ε =0.011	τ _x =0.006; τ _y =0.012; τ _ε =0.013
τ _{TOUSCHEK} (HRS.)	2.8 (2.5 GeV)	3.3**	1.4 (0.7 GeV)
LATTICE STRUCTURE	SEP. FUNCT. TRIPLETS, 8f.	SEP. FUNCT. DOUBLETS, 4f.	HYBRID STRUCT., FODO, 4f.
MAGNET COMPLEMENT	16B (2.7 m.) 40Q (0.45 m.), 16Q (0.8 m.) 32S (0.2 m.)	8B (1.5 m.) 24Q (0.3 m.) 12S (0.2 m.)	8B (1.5 m.) (+defoc. comp.) 8Q (0.3 m.) (foc. elem. only) 4S (0.2 m.)
NOMINAL TUNES ν _x , ν _y	9.7, 5.7	3.3, 1.3	2.4, 1.4
MOMENTUM COMPACT., α _p	0.0065	0.023	0.106
RF, FREQUENCY (MHz)	52.880	52.880	52.880
RADIATED POWER (KW)	252+35 N _{WIGGLER}	11.3	0.22
RF, PEAK VOLTAGE (KV)	800	100	20
DESIGN RF POWER (KW)	500 (300 BEAM)	50	0.4
ν _B	0.0042	0.0022	0.0015
ENERGY SPREAD, (σ _ε /E)	8.2 10 ⁻⁴	4.4 10 ⁻⁴	6.4 10 ⁻⁴
NAT. BUNCH, 2σ _L (cm)	10.5	7.6	16.0
EQUIL. ε _x (m.rad)	8.0 10 ⁻⁸	8.8 10 ⁻⁸	4.8 10 ⁻⁸
(K=0.1): ε _y (m.rad)	8.0 10 ⁻¹⁰	8.8 10 ⁻¹⁰	4.8 10 ⁻¹⁰

* τ_x=τ_y=0.26 sec; τ_ε=0.13 sec at 0.7 GeV with V_{eff}=50 kV.

** For V=100 kV at twice the natural bunch length.

Structure and dynamics of the VUV lattice^{8]} is similar to that of the X-ray ring. The parameters of both the X-ray ring and the VUV ring are given in Table 2. The VUV lattice and structure functions are given in Fig. 5 and Fig. 6.

INJECTOR

The injector system for the two storage rings consist of a nominal 100 MeV linear accelerator^{9]} (S band, $2\pi/3$ mode; 2855.7 MHz; 1 pulse/sec; 3 accelerating sections; beam current 20 mA; momentum spread, $\Delta p/p = +0.25\%$, beam emittance $\pi\epsilon = 2 \cdot 10^{-5}$ rad.m.) and a 100-700 MeV booster synchrotron^{10]} of which the parameters are also presented in Table 2. For this synchrotron a hybrid lattice (defocusing gradient "dipole"-focusing quadrupole) has been designed of which the structure is shown in Fig. 7. Notwithstanding the use of combined function elements the betatron and synchrotron oscillations are damped, an essential feature of the booster, since it will be operated with an adequately long high energy dwell time, in order to achieve minimum beam emittance prior to transfer into either storage ring.

Beam injection into the Booster will be done by means of the well known "lossy" multiturn transverse stacking technique. The details of this process have been worked out^{11]} and, typically, for the stated linac parameters, a booster intensity of 23 mA can be achieved readily by means of approximately 17 turn injection, with a net stacking efficiency of 70%.

PRINCIPAL SUBSYSTEMS

Vacuum

Associated with the high linear power density incident on the vacuum chamber walls (for the X-ray ring = 6 kW/m) the magnitude of gas desorption due to synchrotron radiation is the most significant parameter for the vacuum system design. Taking this, a 150°C bakeout, Argon glow discharge cleaning and a certain amount of "self-cleaning" due to the incident radiation, into account, the storage rings have been designed for an operating

pressure of 10^{-9} Torr in order to achieve gas scattering lifetimes in excess of 10 hrs. The vacuum chambers are fabricated from Aluminum extrusions, patterned after the SPEAR chamber design. Here, however, two cooling channels are incorporated, as shown in Fig. 8 in order to provide for simple geometries to pass the synchrotron radiation to the external photon lines. This also makes possible a simple crotch design (also shown in Fig. 8) for the synchrotron radiation exit port in the X-ray ring which is subject to perpendicular incidence of the radiation with a linear power density of 36 kW/m.^{12]} (Note: LEP, 100 GeV e^- , $P_{Lin.} = 1.5$ kW/m.)

Magnets

Inherent in the objective of providing for ease of synchrotron radiation emergence, C magnets are used for the dipole magnets. The basic cross section^{13]} is shown in Fig. 9. All magnets are built up from stamped laminations. These are glued together in elementary blocks of parallelogram cross section, which in turn are assembled into complete units with parallel end faces. End shims, shaped to control the integrated sextupole term, are used. For the VUV ring dipole magnets the field distributions are given in Fig. 10. Related to the strong curvature of these units ($\rho = 1.91$ m.) the azimuthal and transverse field distribution exhibit significant variation with excitation associated with the effective narrowing of the pole and consequent enhanced saturation towards the ends of the magnet. This is not expected to be the case for the X-ray ring ($\rho = 6.87$ m).

FIG. 9 VUV, X-RAY RING, DIPOLE CROSS SECTION

FIG. 10. FIELD DISTRIBUTION OF THE VUV DIPOLES

Computer Control

The NSLS facility will be controlled and monitored through a computer network consisting of two Data General ECLIPSE S250 computers connected to 3 Data General NOVA 3/4 computers, each of which in turn is linked via serial lines to 16 microcomputers.^{14]} The basic network is illustrated in Fig. 11. As indicated, two identical, connected, control terminals will be used, each fully capable of addressing all functions of the two accelerators and two storage rings. This approach permits more readily extensive program development simultaneously with facility operations.

For the external photon lines individual computers will be used ranging from, typically, a limited capability Textronix 4051 system for certain photoelectrospectroscopy lines in the VUV area to a VAX 11/780 system for biological structure research using the X-ray small angle scattering line.

Rf Systems

For the acceleration systems a relatively low frequency of 53 MHz has been adopted partly for cost and in-house technology reasons, partly by considering the objective of a minimum over voltage factor (for fixed quantum lifetime, $eV_c/U_0 = q \alpha_p (\alpha_p R/E) f$) in order to minimize the required lattice straight section length for rf structures; the desirability of a low synchrotron oscillation wave number ($v_{s0} \alpha_p R/\rho)^{1/2} E^{3/2} f$) so that potential betatron-synchrotron resonant side bands, which constrain the permissible betatron oscillation frequencies, may be avoided; the desire to reduce heavy beam loading of the rf cavity in order to improve stability of operating conditions (lower shunt impedance guided by reasonable cavity excitation power); and the objective to avoid clearing electrodes in the storage ring vacuum envelope (impedance problem), taking into account that beam neutralization¹⁵⁾ occurs for $I_{st} < I_{ar}$ where $I_{st} \propto f^2$ (e.g. for the X-ray ring, $I_{st} \approx 0.1A$ for H_2).

Taking into account the experimental objective of dynamic spectroscopy studies whereby bunch length values as low as 0.1 nsec may be desired in specific cases, the choice of a lower frequency is in general undesirable ($\lambda_b \propto (\alpha_p R) E^{-1/2} f^{-1}$), however, in the NSLS designs this is greatly offset by the use of very low α_p lattices, the freedom to increase V_c , the rf cavity voltage, and the intended use of an harmonic cavity to decrease the bunch length for lower intensity runs for fluorescent lifetime measurements.

A single cavity will be used in each storage ring. For the X-ray ring, the structure is illustrated in Fig. 12, for the VUV ring exactly half this structure will be used. For cost reasons, arbitrarily, a maximum value of 300 kW beam power has been adopted for the X-ray ring, in effect limiting the operating current to a somewhat lower design value when using four high field multipole wigglers (see Table 2). For the X-ray ring cavity a 0.5 MW drive system will be used by combining four grounded grid tetrode, 125 kW power amplifiers. These units have been individually tested up to 150 kW; consequently with a calculated cavity power dissipation of 150 kW, the stated beam power requirements can be met. For the VUV ring, a similar, but single output stage, 50 kW power amplifier will be used, adequate

FIG. 11. NSLS CONTROL NETWORK

FIG. 12. NSLS X-RAY CAVITY

for the nominal 5 kW cavity power dissipation plus approximately 12 kW beam power requirement.

For the booster synchrotron, a simple two gap coaxial structure will be used. With a design current of 20 mA and energy loss per turn of 11 keV, the required beam plus cavity power of nominally 1 KW will be met with a 3 KW drive stage.

SPECIAL COMPONENTS

Wigglers and Undulators

In order to extend the photon energy available from the X-ray ring to energies in excess of 100 keV, superconducting wigglers will be incorporated in four of the lattice long straight sections. The structural parameters for the NSLS wigglers are $\hat{B} = 6T$, 7 pole structure, magnet period 17.4 cm, gap 2 cm, NbTi conductor. The source parameters are given in Table 1 and a cross sectional view of the structure is given in Fig. 13.

An undulator or multipole coherent wiggler^{16]} is a structure consisting of many low field wigglers in sequence. Its basic objective is the generation of high photon flux, quasi monochromatic peaks in the synchrotron radiation frequency distribution given by (median plane): $\lambda_k = \lambda_w (2 k \gamma^2)^{-1} (1 + K^2)$ with $K = 0.1 B \lambda_w$ (KG, cm) and $k = 1, 3, 5, \dots$. 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. For the VUV storage ring an undulator is planned for which a possible photon flux, at $\lambda = 400 \text{ \AA}$ ($k = 1$) of approximately $8 \cdot 10^{16} \text{ ph/sec/1\AA/1\% } \Delta\lambda/\lambda$ has been calculated^{17]} using a $n_w = 50$ structure ($B = 0.4 \text{ T}$, $\lambda_w = 5 \text{ cm}$, $g = 3 \text{ cm}$, $K = 2$).

Free Electron Laser Experiment

By complementing the undulator structure with reflecting mirrors, it becomes feasible to set up conditions whereby the relativistic electrons in the storage ring exchange energy with the multiple reflected radiation so that the electromagnetic wave gains energy from the circulating electrons, thereby creating a so-called Free Electron Laser (FEL) structure. While the operation of a FEL with single passage of electrons has been verified experimentally^{18]}, only limited evidence exists with a circulating electron beam-FEL

FIG. 13 NSLS SUPERCONDUCTING WIGGLER

FIG. 14 FREE ELECTRON LASER EXPERIMENT

combination. This stimulated^{19]} the development of a FEL experiment to be carried out with the NSLS VUV storage ring with the objective of an existence proof of a modest power, tunable, laser for research applications in the UV(1000-3000 Å) region. The tentative parameters for this experiment are: wavelength 2600 Å; E = 500 MeV, undulator as above, but B = 8.2 kG, K = 3.1, laser cavity length 8.5 m, rms laser beam radius 0.3 mm, gain per pass 15%. In addition to the study of a superconducting undulator for this purpose, the alternative of a permanent magnet undulator is being studied. The optical cavity structure for this FEL experiment is shown in Fig. 14.

STATUS OF THE PROJECT

NSLS building construction is nearing completion, the VUV storage ring is in place, the linear accelerator is now being installed and the booster synchrotron installation will commence this coming August. Installation of the X-ray ring will start during October of this year. As part of the NSLS construction phase eight instrumented monochromatized photon lines for both the X-ray ring and the VUV ring are under construction. Approximately 15 instrumented beam lines will be built by "Participating Research Teams" both from within and from outside of Brookhaven National Laboratory. Plans for these additional instruments are well advanced with major installation to commence in the course of 1981. Completion of construction is expected by the fall of 1981 with the turn over of both storage rings to experimental utilization.

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