Wiggler, Undulator, and Free-Electron Laser-Radiation Sources Development

at the National Synchrotron Light Source*

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Abstract

An overview is presented of the special radiation sources development at the NSLS for incorporation in a 2.5 GeV X-ray storage ring and a 700 MeV VUV storage ring. This includes a superconducting high field multipole wiggler, $\lambda_c = 0.5\text{\AA}$; a permanent magnet wiggler, $\lambda_c = 2.0\text{\AA}$; a maximum photon energy undulator (5-7 keV); an undulator for a soft X-ray line or "continuum" spectrum and a free electron laser source tunable in the 2500 - 4500\text{\AA} region. Source characteristics and status of development are given. In addition, the incorporation of a backscattered Compton photon source is being studied and relevant parameters are presented.

Introduction

Two electron storage rings have been constructed at Brookhaven National Laboratory for the generation of intense fluxes of synchrotron radiation in the VUV wavelength region (700 MeV e^- storage ring, $\lambda_c = 31.5\text{\AA}$) and in the X-ray wavelength region (2.5 GeV e^- storage ring, $\lambda_c = 2.5\text{\AA}$). In the earliest stage of design of these storage rings, the incorporation of special radiation sources, such as wiggler sources and undulator radiation sources was planned for and straight sections of adequate length were designed into the storage ring magnetic lattice structure

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for these purposes. Also, freedom of betatron tune choice was incorporated so that the optical properties (β function distribution in the long straight sections) could be optimized for the special radiation source to be employed. The choice as to what type of sources should be included in the NSLS storage rings is principally guided by experimental demand. This may range from the desire for maximum energy photons (inclusion of superconducting wigglers) to the objective of extreme collimated photon flux in a limited wavelength region (inclusion of undulators). Present NSLS development is aimed at including the maximum number of special radiation sources possible constrained by the number of free straights. This will include superconducting wigglers, permanent magnet hybrid wigglers, undulators, a free electron laser source and a Compton backscattered photon source for the generation of monochromatic γ rays. Details of these elements, of which some are in the construction stage and some in an advanced developmental stage, are given below.

For completeness sake, the following summarizes the basic NSLS structure (arc sources) as a synchrotron radiation source: The facility consists of a 70 MeV Linear Accelerator--700 MeV Booster Synchrotron Injector combination; a 700 MeV, 1 Ampere, e^- storage ring for the VUV domain and a 2.5 GeV, 0.5 Ampere, e^- storage ring for the X-ray domain. The VUV ring has eight 75 mrad ports and eight 90 mrad ports. The X-ray ring provides for $(28-N)$, 50 mrad ports of which each will normally be split in two (or more) branches, subtending typically 10 mrad (or less) of orbit arc per branch, (N is the number of special radiation sources in the X-ray ring, $N = 8$). Basic source parameters for both the X-ray and VUV

rings are given in Table 1, the photon flux vs. wavelength spectra for the arc sources are given below in Fig. 4, Fig. 7 and Fig. 10 and the overall arrangement of the NSLS facility is given in Fig. 14.

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

WAVELENGTH ($\text{\AA}$)	X-RAY (Arc)	VUV (Arc)
$[\lambda_c(\text{\AA}); \epsilon_c(\text{keV})]$	10 [2.5 ; 5.0]	100 [31 ; 0.4]
SOURCE DIMENSIONS		
$2\sigma_x \times 2\sigma_y$ (mm ²)	0.2 x 0.5	0.2 x 0.55
ARC LENGTH, $\Delta x'$ (MRAD)	10	60
VERT. OPENING ANGLE (MRAD) (2 σ')	0.4	1.4
FLUX, PER 0.1% $\Delta\lambda/\lambda$ (PH/SEC)	$2.5 \cdot 10^{14}$	10^{15}
TIME STRUCTURE		
NUMBER OF BUNCHES	30	9
ORBITAL TIME (NSEC)	568	170
EFFECTIVE BUNCH LENGTH (NSEC)	1.7	1.1

X-ray Wiggler Sources

Since the critical photon energy (ϵ_c) is proportional with the B field magnitude ($\epsilon_c = \text{Const. } B^2$), the critical energy, and with that the available photon flux in the region $\epsilon > \epsilon_c$ (arc) can be substantially increased with the use of wiggler magnets. These devices^{1,2} perturb the electron orbit locally, typically in a sinusoidal segment trajectory with a maximum local B field of $B_w \gg B_{\text{arc}}$. In order to extend the photon energy available from the X-ray ring to energies in excess of 100 keV, a high field superconducting wiggler has been designed³ and is presently in the testing stage. The basic parameters are as follows: 5 poles at 6 T., 2 end poles at 3.9 T., period length, $\lambda_w = 17.42$ cm; full gap magnetic 3.2 cm, full gap beam stay clear 2.0 cm; magnetic deflection parameter $K = 0.934 B_0 \lambda_w = 97$. In order to utilize maximum current density in the superconducting NbTi conductor the coil package per pole is made up in two winding layers, as follows: Inner layer, wire 1.06 mm ϕ , $J = 17.3$ kA/cm²,

$B_c = 8.5$ T; outer layer, wire 0.74 mm ϕ , $J = 35.3$ kA/cm², $B_c = 5.7$ T.

This unit has been tested in a provisional dewar and a median plane field of 6 T has been achieved. A cross section of the wiggler is shown in Fig. 1 and the photon flux vs. wavelength spectrum is given in Fig. 4 and Fig. 7.

For a specific electron beam energy, the high fields employed in a superconducting wiggler, in order to achieve high ϵ_c values, have a significant drawback, since the photon source size is enhanced in opening angle proportional to K/γ and the cross sectional magnitude (for small observation angles) proportional to $\lambda_w K/(\pi\gamma)$. This reduces the source brightness and in practical structures limits the available photons to a fraction of the total generated by the wiggler source. With an external acceptance θ_{ext} , the fraction of energy emitted within θ_{ext} is given by

$$P_f = 3.17 \pi \lambda_w E^2 B_0^2 I (F(\alpha)) \quad \text{with}$$

$$F(\alpha) = (2/\pi)(\alpha + 1/2 \sin 2\alpha) \text{ and} \quad \sin \alpha = \theta_{1/2,ext}/(K/\gamma)$$

which for the NSLS X-ray superconducting wiggler; with $B = 6$ T, $n = 5$ poles, $\theta_{ext} = 10$ mrad; yields $P_{w,tot} = 31$ kW (end poles neglected) and $P_{f,ext} = 9.7$ kW. It is obvious, therefore, that if maximum photon energy is not the prime objective, more favorable wiggler structures can be designed with larger number of poles per unit length, smaller radiation opening angle and smaller effective source size. A wiggler design which meets these objectives in a beautiful manner is the Vanadium-Permendur-Rare Earth Cobalt (REC) permanent magnet hybrid wiggler. This device⁴, invented by K. Halbach (LBL), emerged from the permanent magnet undulator design⁵. An undulator is a structure consisting of many low field one pole wigglers

in sequence with the characteristic that it generates coherent radiation from the multiplicity of poles.⁶ The basic structure of a permanent magnet undulator is shown in Fig. 2. The structure, as shown, is suitable for low field undulators (see below). The field on axis is given by:

$B = \text{const. } B_r \exp(-\pi g/\lambda_w) \cdot F(\text{geometry})$, with g = undulator gap, B_r = remanent field, magnet material and $F(\text{geometry}) = 0.5-0.8$ for various structures. The maximum field is apparently limited by the ratio (g/λ_w) and B_r , a basic permanent magnet material property. It was realized, however, that by cascading the permanent magnet blocks and "guiding" the combined field flux through high μ poles, a much larger on axis field could be obtained without sacrificing magnetic period length. This is illustrated in Fig. 3 where the design principle and engineering execution of an extremely simple, low cost, fixed gap hybrid wiggler structure is shown. The parameters of this wiggler are as follows: 23 poles at 1.5 T (2 end poles at reduced field); $\lambda_w = 13.6$ cm; full gap, magnetic, 2.0 cm, full gap beam stay clear 1.8 cm; magnetic deflection parameter $K = 19$, $2\theta_{1/2} = 7.8$ mrad, $2\theta_{1/2, \text{eff}} = 4.6$ mrad ($B \geq 0.8 B_0$), orbit amplitude deviation (p-p) = 0.16 mm. The photon flux vs wavelength spectrum is shown also in Fig. 4 and Fig. 7. With its λ_c at 2.0Å and 23 full field poles it provides for substantial flux in the wavelength region of 0.5-3Å where the sharp fall off of the arc source spectrum occurs.

Both the superconducting wiggler and hybrid permanent magnet wiggler are in an advanced stage of construction and are expected to be installed within the next year in the X-ray storage ring. In addition to these wiggler sources, because of the experimental interest⁷ in a high flux source in the 0.3-1Å region, with minimum opening angle; a superconducting wiggler

design with maximum median plane field values of 3 T is being studied.

Tentative parameters are: $B = 3T$, $n = 15$ poles, $\lambda_w = 8$ cm, $K = 22$, gap 2 cm.

A distinct drawback of high field wigglers is the large magnitude of total radiation power generated, which creates problems of optical stability in the external photon lines (mirror distortion) and drift in the spectral output of the monochromators. When compared with the superconducting wiggler, the hybrid wiggler total radiation power is substantially less, i.e. 4.4 kW; however, this power is radiated within an opening angle of ≈ 7.8 mrad and the radiation power per unit arc is actually higher than for the superconducting wiggler (see Table 3).

X-ray Undulator Sources

Initially the basic objective in the utilization of an undulator source was the generation of a quasi monochromatic line spectrum given by $\lambda_k = (\lambda_w/2k\gamma^2)(1 + \frac{K^2}{2} + \gamma^2\theta^2)$ and the on axis source brightness enhancement ($\propto N^2$, where N is the number of undulator periods).⁸⁻¹⁰ Subsequently, the uniqueness of an undulator source used in a high energy electron storage ring was recognized because it provides for a radiation source with extreme collimation, $\theta_{1/2} = (1/\gamma)$, and with a high ratio of useful photons per total radiation power generated, as expressed by

$$P_u(k=1) = P_u \left(1 + \frac{K^2}{2}\right)^{-2} \quad \text{with} \quad P_u = 1.9 \cdot 10^{-8} N \gamma^2 K^2 I / \lambda_0$$

where $P_u(k=1)$ is the total power generated in the $k=1$ mode, and P_u is the total power radiated by the electrons traversing the undulator.

$$[\text{Alternatively: } dP(w=w_1)/(dw/w) = 3 P_u (1 + \frac{k^2}{2})^{-2}]$$

This suggests the use of undulators with very low K values in order to reduce the heating of optical elements by photons outside the spectrum region of interest (say $k = 1$). However, this tends to limit the available spectrum to higher wavelength values because of the rapid fall off of the spectrum with large undulator mode, k, numbers. Higher photon energy can, of course, be obtained from the undulator by using small magnetic period, λ_w , values. This, however, is limited because of the exponential dependence of B_0 on (g/λ_w) and the undulator structure minimum gap value is limited by specific requirements of storage ring design; such as minimum gap value associated with the magnitude of the beam quantum lifetime $((g/2) > 8 \sigma_y)$, beam life time associated with rest gas scattering $(1/\tau \sim \gamma^{-2} g^{-2})$ and enhancement of the growth rate for the transverse resistive wall instability $(1/\tau \sim \beta_0 g^{-3})$. (For the NSLS storage ring these considerations suggest a minimum gap: X-ray, $g \geq 8$ mm; VUV, $g \geq 14$ mm. In effect, therefore, the highest photon energy available, with suitable choice of the undulator K value, is set by the minimum gap the storage ring tolerates, without deleteriously affecting normally achievable beam intensity. Having adopted a minimum gap value, the choice of undulator parameters is narrowly guided by the desired spectrum range, radiation opening angle, heating of optical elements and desire for optimum source brightness. With the above considerations taken into account, the parameters for a high energy undulator, $2\lambda < 12\text{\AA}$ (HEU) and for a soft X-ray undulator $6 < \lambda < 60\text{\AA}$ (SXU) have been developed and preliminary design studies have been carried out. The parameters for these units are tabulated in Table 2

and the undulator spectra are given in Fig. 5. In this figure the spectral structure of the HEU undulator is shown in detail. For the SXU undulator the mean photon flux versus wavelength is given, since for higher K values (and integrating over all radiation angles) the line spectrum aspects of the undulator is strongly reduced. This is also shown in Fig. 6 where the true spectral structure is given for the SXU undulator. It is evident that for the undulators the ratio $(N_{\max}/N_{\min})$ vs λ approaches unity for higher undulator K values. This can be expressed as follows: For $K \gg 1$, the value of k_c is given by $(3/8)K^3$, where k_c is the harmonic number of the critical frequency ($\omega_c = k_c \omega_1$). Since at ω_c many undulator harmonics, k , contribute the magnitude of $(N_{\max} - N_{\min})/N \propto (1/k_c)$ or $\propto K^{-3}$.

Intercomparing the spectra and parameters of these two undulators it shows, that the spectral coverage of the HEU, $K = 1.4$ and the SXU, $K = 3$ is quite similar in the 2-12Å region. The total undulator radiated power is similar ($\propto NK^2/\lambda_w$), for fixed total undulator length, but the opening angle of radiation is a factor of two less for the HEU unit. In this case, however, the HEU undulator must operate with a gap value as low as 11 mm in the X-ray storage ring, which may not be possible. Accepting, however, an order of magnitude less flux from the HEU unit above 2-3 keV, and the strong line spectrum nature, as compared with the SXU unit; when set, with an acceptable gap value at approximately 20 mm, at $K = 0.5$, it provides for an extreme collimated ($2\theta_{1/2} = 1/\gamma = 0.2$ mrad), lower total power (reduced by an order of magnitude), high brightness (see below) undulator source in the spectral region (tunable) around ~2 keV (~6Å).

Table 2. UNDULATOR PARAMETERS (X-RAY)

	HEU	SXU
STRUCTURE	VP-SnCoS HYBRID	
NUMBER OF PERIODS	80	40
PERIOD LENGTH λ_w	3.0 cm	6.0 cm
FULL GAP (MAGN. = STAY CLEAR)	5-25 mm. VARIABLE	
FULL GAP, OPERATIONAL OBJECTIVE	10 mm	
UNDULATOR LENGTH	2.5 m	
DEFLECTION PARAMETER	1.7-0.6	5.0-3.0
GAP	10-20	10-20
$2\sigma_{\theta_y}$	0.7-0.25 mrad	2.0-1.2 mrad

X-ray Source Comparison

The theoretical performance parameters of the various special radiation sources for the X-ray ring, as mentioned above, have been evaluated in terms of photon flux,^{11,12} central "brightness" at the critical frequency $[dN/d\phi d\psi(dw/w)]_{\psi=0, w=w_c} = B_{\psi=0}(w=w_c)$; and average source brightness¹³ at the critical frequency,

$$[dN/\text{unit area source}/\text{unit solid angle}/(dw/w)] = \langle B \rangle_{w=w_c}$$

and have been compared with the X-ray arc source parameters. Relevant expressions for this have been gathered and are listed in the Appendix. Associated with the inherent length of the wigglers and undulators the "depth of field" broadening¹⁴ of the sources have been taken into account by using appropriate expressions for the effective source cross section and radiation angles. The results of this evaluation are given in Table 3. The results are, in general, self-explanatory, indicating now quantitatively for realizable wigglers and undulators the significant flux and brightness enhancement achievable when compared with an X-ray arc source. The $\langle SB \rangle_{w=w_c}$ for the wigglers have been calculated taking instead of the total radiation angle available, (K/γ) , a more realistic fraction of

TABLE 3. NSLS SPECIAL RADIATION SOURCES (E = 2.5 GeV; I = 0.5A)

SOURCE	B kG	c_c keV	$(dP/d\theta)_{MAX}$ W/MRAD	$^{(1)}F_0(\alpha)$	FLUX ($\times 10^{14}$) $\frac{PH/s/MRAD/1\% \frac{d\omega}{\omega}}$ AT $\lambda=\lambda_c$, ALL γ	$^{(2)}B_0(\times 10^{14})$ $\frac{PH/s/MRAD^2/1\% \frac{d\omega}{\omega}}$ AT $\lambda=\lambda_c$, $\gamma=0$	$^{(3)}\langle SB \rangle (\times 10^{15})$ $\frac{PH/s/MRAD^2/MM^2/1\% \frac{d\omega}{\omega}}$ AT $\lambda=\lambda_c$
(ARC	12.2	5.1	40.1	--	2	3	2)
<u>LHW</u>	15.0	6.2	1198	16.5%	48	74	⁽⁵⁾ 4.5
<u>SUN1</u>	60.0	24.9	998	3.2%	10	⁽⁴⁾ 15/2	⁽⁵⁾ 9.3
SUN2	30.0	12.5	1490	14.1%	30	46	⁽⁵⁾ 14

	$2\theta_{1/2}$ MRAD	c_1 keV	P_u kW	$\frac{P_w/P_u}{(P_w/P_u)}$	$F_0(\alpha)$	FLUX ($\times 10^{14}$) $_{\omega_1}$ $\frac{PH/s/1\% \frac{d\omega}{\omega}}$	$B_0(\times 10^{14})_{\omega_1}$ $\frac{PH/s/MRAD^2/1\% \frac{d\omega}{\omega}}$	$\langle SB \rangle (\times 10^{15})_{\omega_1}$ $\frac{PH/s/MRAD^2/MM^2/1\% \frac{d\omega}{\omega}}$
HEU	0.57	1.0	1.2	0.26	100%	570	1400	260
SXU	1.2	0.18	1.4	0.03	91%	470	150	28

⁽¹⁾ $F_0(\alpha)$ = FRACTION OF TOTAL WIGGLER/UNDULATOR RADIATED POWER IN (WITHIN) 1 MRAD, AT $\theta_{OBS} = 0$.

^{(2),(3)} DEFINITION, SEE TEXT. ⁽⁴⁾OBSERVATION CENTERED ON $X = \pm K\lambda_0/2\pi\gamma$. ⁽⁵⁾ $\theta_{1/2,EXT} \leq 5$ MRAD.

the radiation flux within an external acceptance angle of $\theta_{1/2, \text{ext}} = 5$ mrad. Also, for the case of the high field wigglers transverse source splitting will occur since $(\lambda_0/2\pi)(K/\gamma)$, the electron orbit maximum deflection in the wiggler, is $\gg \sigma_x$, resulting thereby in two distinct domains of high photon density in the photon source phase space distribution. In the central "brightness" magnitude for the SUW1 source, as listed, this is approximated by dividing the peak brightness value by a factor of two. The advantages of the undulators as special radiation sources is evident from these results, both in terms of flux, on axis "brightness" and average brightness. Although the total flux available (at $w=w_1$) for the HEU and SXU undulators are similar, the source brightness values are an order of magnitude larger for the HEU undulator, when compared with the SXU undulator.

Taking specifically also spectral coverage into account, an alternative comparison of the various X-ray sources has been made by assuming an experimental beam line horizontal acceptance angle of 5 mrad

and comparing $dN/(\frac{dw}{w})$ vs wavelength for the arc, wigglers and the SXU source. This is shown in Fig. 7. Both the results listed in Table 3 and in Fig. 7 indicate the desirability of having a variety of sources available, as listed, in order to meet various experimental demands.

VUV Undulator Sources

The VUV ring permits inclusion of two special sources in its magnetic lattice structure. One of the straight sections will be used for a Free Electron Laser experiment and is expected to evolve as a special FEL source for experimental usage. The undulator for this experiment,

presently in final stages of assembly, can, however, also be used as a generator of "natural" undulator radiation. The parameters of this undulator are as follows: Permanent magnet (SmCo_5) structure, $N = 38$, $\lambda_w = 6.5$ cm, variable gap 1-6 cm, deflection parameter $K = 4.3-0.4$; for $g = 2.0$ cm, $K = 2.4$, $2\theta_{1/2} = 3.5$ mrad. A cross section of the undulator is shown in Fig. 8. Its spectrum, at $E_e = 0.7$ GeV, is given in Fig. 9 for $K = 1$, integrated over all ψ angles but for fractional horizontal acceptance, $\gamma\theta = K/2$. Alternatively, its spectrum, for $K = 2.4$, integrated over all angles, is essentially identical to that shown in Fig. 6 for the X-ray ring, except that its wavelength scale is shifted by a factor of approximately 10 towards larger wavelength. For the latter case, compared with the regular VUV arc source, as shown in Fig. 10, when used in a mode of 10 mrad external acceptance, the undulator provides for a factor of 400 flux enhancement in the 200-2000Å spectral region. In terms of source brightness the undulator parameters are summarized in Table 4, where the same notation is valid as used in Table 3 and the Appendix.

Although it is planned to use the VP-REC hybrid wiggler in the X-ray ring, its spectral output when placed in the 0.7 GeV VUV ring is of interest when compared with the VUV arc source. This is also shown in Fig. 10. Compared both with the undulator and the arc source it provides for substantial flux enhancement in the spectral region of 20-100Å where high throughput monochromators are difficult to achieve.¹⁵ If the spectral region above 200Å is of experimental interest, the undulator provides for a more favorable source both in terms of source brightness and lower total radiation power output (factor of 10) when compared with the hybrid wiggler.

TABLE 4. NSLS SPECIAL RADIATION SOURCES ($E = 0.7$ GeV; $I = 1A$)

	$2\theta_{1/2}$ mrad	ϵ_1 eV	P_e kW	(P_{u1}/P_u)	$\frac{P}{\omega}$ (%)	$\frac{Flux (\times 10^{14})_{\omega_1}}{Ph/\omega / 12 \frac{d\omega}{\omega}}$	$\frac{B_0 (\times 10^{14})_{\omega_1}}{Ph/\omega / mrad^2 / 12 \frac{d\omega}{\omega}}$	$\frac{\langle SB \rangle (\times 10^{15})_{\omega_1}}{Ph/\omega / mrad^2 / m^2 / 12 \frac{d\omega}{\omega}}$
FEL U.	3.5	18	0.12	0.07	37%	806	309	4.6
	(6-60)							

The Free Electron Laser Source

In the course of developmental work at the NSLS towards brighter and higher flux radiation sources in association with the NSLS electron storage rings, it was realized that combining the Free Electron Laser concept with the unique properties of the high current stored electron beam in the UV ring, i.e., low beam emittance, small beam energy spread and large peak current, could lead to a very high brightness, high flux, special radiation source in the 2000-4000Å region.¹⁶ While the operation of a FEL with single passage of electrons has been verified experimentally¹⁷ only limited experimental results are available of a circulating beam driven FEL. Consequently, a proof of principal experiment was proposed and is presently being carried out.¹⁸ The experiment will be done in two phases, i.e. the amplifier experiment and the oscillator experiment. In the amplifier mode the laser beam from an external argon ion laser will be directed through the electron beam undulator interaction region and the single pass gain will be measured. Subsequently, the optical cavity will be completed by means of end mirrors and the laser oscillating mode will be established. The experimental arrangement is shown in Fig. 11. Principally, in the free electron laser, the circulating electron beam of the storage ring exchanges energy with the laser radiation field in the presence of an undulator in which the electrons execute transverse oscillations. With the laser beam

propagating coaxially with the electron beam, the oscillating transverse electric field of the laser can exchange energy with the transverse oscillating electrons provided that the laser field is phased correctly relative to the electron oscillations. The resonance condition is given by $\lambda = \lambda_u(1 + K^2/2)/(2\gamma_r^2)$ with $\gamma_e = \gamma_r$, i.e. the condition for energy transfer is that the radiation wavelength is close (but not equal) to that of the wavelength of "natural" undulator radiation. The electromagnetic field energy gain per pass through the undulator interaction region, within specific limits of electron beam energy spread and angular divergence, is given by:

$$G = (\Delta\epsilon^2/\epsilon^2) = 4.5 \pi^2 \gamma_r^2 \lambda_u^2 N_u^3 k^2 (1+k^2)^{-2} (I_p/I_A) \Sigma_{hv}^{-1}$$

with $k = (K_u/\sqrt{2})$, I_p = peak electron current, $I_A = 17.10^3 A$, and $\Sigma_{hv} = \Sigma_e$, the electron or photon beam cross section. The laser field energy increases exponentially as $\exp(Gn)$, where n is the number of traversals, as a consequence of the progressive increasing electron beam energy spread. Net zero gain occurs when the electron beam energy spread is given by $(\Delta E/E) \approx 1/(2N_u)$. The increase of $(\Delta E/E)$ is counterbalanced by the synchrotron radiation damping, leading to a steady state condition whereby the laser power is given by $P \approx U_0 I_0 / 2N_u$ where U_0 is the total synchrotron radiation power radiated.¹⁹ The line width of the laser radiation is given by $(\Delta w/w) = \lambda/\sigma_{//}$ where $\sigma_{//}$ is the electron bunch length.

The FEL experimental parameters are given in Table 5. Taking $\lambda = 3000A$, $\sigma_{//} = 6$ cm, $U_0 = 3$ keV, $\langle I \rangle = 1A$, $\eta = 1\%$, results in $(\Delta w/w) \approx 5 \cdot 10^{-6}$, $P_{ext} \approx 10$ W.

In terms of photon flux and source brightness the relevant quantities are given in Table 6, together with the corresponding values for the FEL undulator as a "natural" undulator source. The uniqueness of the FEL as a special radiation source is evident from this comparison. Compared with, in present terms, a high brightness undulator source, its flux spectral density is six orders of magnitude higher and its source brightness value six to seven orders of magnitude higher. In addition, its line width $(\Delta\omega/\omega) = 5 \cdot 10^{-6}$, truly a monochromatic source when compared, typically, with the undulator natural radiation first order line $(\Delta\omega/\omega = 1/N = 10^{-2})$.

The present FEL development focuses on the 2500-4500Å region, partly set by storage ring parameters, partly by the reflectivity fall off of the FEL cavity mirrors below 2500Å. Eventually, it is planned to extend development into the spectral region below 2500Å.

TABLE 5. FEL EXPERIMENTAL PARAMETERS

e⁻ STORAGE RING:		LASER CAVITY:	
ENERGY	300-500 MeV	L_c	37.0 m
INTENSITY	3A, AVERAGE, 3 BUNCHES	CAVITY LOSS, 3520 Å	2%
U_0 /TURN	0.4-3.2 keV	WAIST, w_0	0.37 mm
UNDULATOR:		FEL EXPECTED PERFORMANCE:	
FIELDS	PERMANENT MAGNETS	λ	2500-4500 Å
$\vec{B}$	0.1-0.7 TESLA	G_0 (SMALL SIGNAL GAIN PER PASS)	6-10%
PERIOD	$\lambda_u = 6.5$ cm, $N=30$	OSCILLATOR POWER	5-15 W
GAP	1-5 cm	LINE WIDTH, $\Delta\omega/\omega$	10^{-6}

TABLE 6. NSLS SPECIAL RADIATION SOURCES, FEL VS UNDULATOR

	$2\theta_{1/2}$	ϵ	P	Flux	B_0	$\langle SB \rangle$
	mrads	eV	W	$Ph/s/10^{-6} \frac{d\omega}{\omega}$	$Ph/s/(0.1 \text{ mr})^2/10^{-6} \frac{d\omega}{\omega}$	$Ph/s/(0.1 \text{ mr})^2 \text{ m}^2/10^{-6} \frac{d\omega}{\omega}$
UNDULATOR (FEL)	3.5	18	120	$8 \cdot 10^{12}$	$3 \cdot 10^{10}$	$5 \cdot 10^9$
FEL SOURCE	0.3	6.2	10	$3 \cdot 10^{18}$	$3 \cdot 10^{16}$	$7 \cdot 10^{16}$

Compton Photon Source

In the development of the structure for the FEL experiment it became evident that by suitable displacement of the lasing cavity head-on encounters could be produced between the oscillating FEL photon bunches and the circulating electron bunches in the VUV ring, resulting in hard γ radiation as a result of the Compton backscattering. Depending on the FEL wavelength, or, when using an external laser, the laser wavelength, γ energies of up to 30 MeV could be made available. This stimulated the development of a higher energy γ source, by combining an external laser with the X-ray ring, of greater interest to a possible medium energy nuclear physics program.²⁰ From kinematical considerations of the photon-electron head-on collision²¹ the various quantities of interest, i.e., backscattered photon energy, resolution, flux and polarization can be derived. The relevant equations are summarized in Table 7. Assuming now either the use of an external Argon ion laser or the use of the radiation from the VUV ring FEL source²², γ radiation of up to 500 MeV can be generated. This is shown in Fig. 12. Energy resolution would be enhanced by means of scattered electron momentum determination ("tagging"). The presently developed experimental arrangement plus set of e^- beam, external laser source and

resulting γ beam parameters²² are given in Fig. 13. Evidently this highly polarized, monochromatic, low background, hard photon source would constitute a unique source for photon nuclear physics.

TABLE 7. COMPTON BACKSCATTERED γ SOURCE

ENERGY: $\epsilon_f = 4\gamma^2 \epsilon_i / (1 + 4\gamma \epsilon_i + \theta^2 \gamma^2)$
 WITH $E_e = \epsilon_f (m_e c^2)$; $\epsilon_i = \epsilon_i' (m_e c^2) = \hbar \nu_i = E_{\text{photon}}$

RESOLUTION: $(\Delta \epsilon_f / \epsilon_f) = \theta^2 \gamma^2 / (1 + 4\gamma \epsilon_i + \theta^2 \gamma^2)$ $\theta = \theta_e + \theta_i$
 WITH θ_e = COLLIMATION ANGLE; θ_i = ELECTRON BEAM DIVERGENCE

FLUX: $I_f = 2 \int \left(\frac{1}{4\pi} \right) L_{sc} d\Omega$; $L_{sc} = N_e N_{\gamma} f_{sc} / \Sigma$
 WITH $N_e = \langle I_e \rangle (2\pi R) / ec$; $N_{\gamma} = P_{\gamma} / \epsilon_i c$

AND $\frac{d\sigma}{d\Omega} = \left(\frac{r_e}{2} \right)^2 \left[1 + \frac{2\epsilon_i \epsilon_f}{(1 + \theta^2 \gamma^2)} - \frac{2\theta^2 \gamma^2}{(1 + \theta^2 \gamma^2)^2} \right]$

POLARIZATION: $P(\theta) = 1 - \Delta \epsilon_f / \epsilon_f \gamma^2 = 1 - (\gamma \theta)^4$ for $\theta \ll 10^{-4}$ r.

Summary

The special radiation sources, in construction and under development at the National Synchrotron Light Source are summarized in Table 8. The special source distribution, both in the X-ray and VUV ring are given in Fig. 14. The addition of these special high flux, high brightness, sources to the basic NSLS arc sources will provide for a unique experimental capability which should open up new pathways in experimental techniques in such areas as condensed matter physics, spectroscopy of atoms, dynamic spectroscopy, etc.

TABLE 8. SPECIAL RADIATION SOURCES, NSLS

SHW	= SHORT HYBRID WIGGLER, $\lambda_c = 2.0\text{\AA}$, 12 POLES 1 - 100\AA AND ABOVE (10 - 0.1 keV AND BELOW)
$\gamma\gamma\text{-e}$	= PHOTON - ELECTRON COLLISION REGION FOR GENERATION OF HARD COMPTON PHOTONS (UP TO 300 MeV)
HEU	= HIGH ENERGY UNDULATOR FOR GENERATION OF EXTREME COLLIMATED PHOTON BEAMS (~ 0.4 mrad); 2 - 12\AA (6 - 1 keV)
SUV	= SUPERCONDUCTING WIGGLER; $\lambda_0 = 0.174$ m, K = 97, $\lambda_c = 0.5\text{\AA}$; 5P-6T + 2P-3T; 0.1 - 10\AA AND ABOVE (100 - 1 keV AND BELOW)
LW	= LONG HYBRID WIGGLER; $\lambda_0 = 0.136$ m, K = 19, $\lambda_c = 2.0\text{\AA}$, 24 POLES 1 - 100\AA AND ABOVE (10 - 0.1 keV AND BELOW)
SKU	= SOFT X-RAY UNDULATOR FOR GENERATION OF EXTREME COLLIMATED PHOTON BEAMS (~ 1.0 mrad); 6 - 60\AA (2 - 0.2 keV)
FEL	= FREE ELECTRON LASER SOURCE, 2500 - 4500\AA ALTERNATIVE: UNDULATOR RADIATION SOURCE 100-2000\AA. UNDULATOR; $\lambda_0 = 0.065$, K = 2.4 - 0.4, $\epsilon_3 = 7 - 66$ eV, N = 38
UVU	= ULTRA VIOLET UNDULATOR FOR GENERATION OF EXTREME COLLIMATED PHOTON BEAMS IN THE 100-1000\AA SPECTRAL REGION
(SUV2)	= SUPERCONDUCTING WIGGLER, $\lambda_c = 1\text{\AA}$; 15 POLES, $\lambda_0 = 0.08$ m, K = 22)
IN CONSTRUCTION	

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APPENDIX: FLUX, CENTRAL SPECTRAL "BRIGHTNESS" AND AVERAGE SPECTRAL BRIGHTNESS
EXPRESSIONS FOR MAGNET ARC, WIGGLER AND UNDULATOR SOURCES

ARC SOURCE, FLUX: $\frac{d\dot{N}(\omega=\omega_c)}{d\omega} = 0.18 \frac{d\gamma(1/c) \frac{d\omega}{\omega}}{d\omega} \quad [\text{PH/S/MRAD}/\frac{d\omega}{\omega}]$

CENTRAL "BRIGHTNESS": $B_{\gamma=0}(\omega=\omega_c) = 4\pi \cdot 10^{-5} \frac{\gamma}{c} \left(\frac{dP}{d\theta} \right) \frac{d\omega}{\omega} \quad [\text{PH/S/MRAD}^2/\frac{d\omega}{\omega}]$

AVERAGE BRIGHTNESS¹⁵: $\langle SB \rangle_{\omega=\omega_c} = \frac{(d\dot{N})/(2.4)^3 \sigma_x \cdot \sigma_z (\frac{\phi_z}{2})}{\text{WITH } (\frac{\phi_z}{2}) = (\gamma^2 + \sigma_z^2)^{1/2}} \quad [\text{PH/S/MRAD}^2/\text{MM}^2/\frac{d\omega}{\omega}]$

WIGGLER SOURCE, SINUSOIDAL FIELD, POLES n , LENGTH $\frac{n\lambda}{2}$, EXTERNAL ACCEPTANCE θ_{EXT}
FRACTION OF ENERGY EMITTED WITHIN θ_{EXT} : $P_f = 3.17 n \lambda_0 E^2 B_0^2 I F(d)$ WITH
 $F(d) = (2/\pi)(d + \frac{1}{2} \sin 2d)$ AND $\sin d = \theta_{\frac{1}{2}\text{EXT}}/2(K/\gamma)$; $\theta_{\text{EXT}} = 1 \text{ MRAD}$; $[\frac{dP}{d\theta}]_0 = P_f(d=d_0)$

FLUX: $\frac{d\dot{N}_W(\omega=\omega_c)}{d\omega} = \frac{0.404}{c} \left(\frac{dP}{d\theta} \right)_0 \frac{d\omega}{\omega} \quad [\text{PH/S}/\text{MRAD}/\frac{d\omega}{\omega}]$

CENTRAL "BRIGHTNESS": $B_{0,W}(\omega=\omega_c) = 4\pi \cdot 10^{-5} \frac{\gamma}{c} \left(\frac{dP}{d\theta} \right)_0 \frac{d\omega}{\omega} \quad [\text{PH/S/MRAD}^2/\frac{d\omega}{\omega}]$

AVERAGE BRIGHTNESS: $\langle SB \rangle_{0,W}(\omega=\omega_c) = \frac{(d\dot{N}_W)/((2.4) \sigma_{x,\text{EFF}} \sigma_{z,\text{EFF}} (\phi_z/2))}{\text{WITH } 2\sigma_{x,\text{EFF}} = (\frac{n\lambda}{4} \phi_x + 2\sigma_x) ; \phi_x = 2(1/\gamma^2 + \sigma_x^2)^{1/2} + \theta_{\frac{1}{2}\text{ext.}}$
 AND $2\sigma_{z,\text{EFF}} = (\frac{n\lambda}{4} \phi_z + 2\sigma_z) ; \phi_z = 2(1/\gamma^2 + \sigma_z^2)^{1/2}$ } $[\text{PH/S/MRAD}^2/\text{MM}^2/\frac{d\omega}{\omega}]$

UNDULATOR SOURCE, SINUSOIDAL FIELD, N PERIODS, LENGTH $N\lambda_0$

FLUX: $\frac{d\dot{N}(\omega=\omega_1)}{d\omega} = \frac{\pi d}{e} \frac{N I K^2}{(1+\frac{K^2}{2})} \frac{d\omega}{\omega} \quad [\text{PH/S}/\frac{d\omega}{\omega}] ; \omega_1 = \frac{2\pi c}{\lambda_0} \frac{2\gamma^2}{(1+\frac{K^2}{2})}$

CENTRAL "BRIGHTNESS": $B_{0,U} = 4.56 \cdot 10^8 N^2 I \gamma^2 F_1(K) \quad [\text{PH/S/MRAD}^2/\frac{d\omega}{\omega}]$

AVERAGE BRIGHTNESS: $\langle SB \rangle_{0,U} = B_{0,U} / ((2.4)^2 \sigma_{x,\text{EFF}} \sigma_{z,\text{EFF}}) \quad [\text{PH/S/MRAD}^2/\text{MM}^2/\frac{d\omega}{\omega}]$

WITH $\sigma_{x,\text{EFF}}, \sigma_{y,\text{EFF}}$ AS ABOVE, USING $N = \frac{n}{2}$ AND $\theta_{\frac{1}{2}\text{EXT}} = (K/\gamma)$

Fig. 1. NSLS SUPERCONDUCTING WIGGLER

Fig. 2. PERMANENT MAGNET UNDULATOR

$$K = 0.9 B_0 \lambda_w; \quad B = \text{CONST. } B_0 \exp(-\pi y/\lambda_w) \cdot F(\text{GEOMETRY})$$

Fig. 3. "VP - REC" HYBRID, PERMANENT MAGNET WIGGLER
(~15 kg, 24 POLES, $\lambda_p = 13.6$ cm, $K = 19$, GAP = 2 cm)

Fig. 4. NSLS SR SPECTRA, X-RAY RING, 2.5 GeV

Fig. 5. NSLS, SPECIAL SOURCES, X-RAY RING, 2.5 GeV

Fig. 6. NSLS UNDULATOR SPECTRUM, X-RAY, 2.5 GeV
($K = 3$, 40 PERIODS, $\lambda_0 = 6$ cm, $2\theta_0 = 1.2$ MRAD, $\phi = 20$ MP, $\gamma = 3.0$)

Fig. 7. NSLS, SPECIAL SOURCES, X-RAY RING, 2.5 GeV

Fig. 8. UNDULATOR STRUCTURE FOR THE FEL

(PERM. MAGNETS, $\lambda_0 = 6.5$ cm, $B_0 = 0.1 - 0.6$ T., $N = 39$)

$N=38$, $\lambda_w=6.5$ cm; $K=1.0$; $\gamma=1370$; $\gamma\theta=0.5$

Fig. 9. NSLS UNDULATOR ($K = 1$) SPECTRUM, VUV RING

Fig. 10. NSLS SPECTRUM, VUV, 0.7 GeV

Fig. 12. ENERGY RANGE, BACKSCATTERED & SOURCE

Fig. 11. NSLS FEL EXPERIMENT

Fig. 13. COMPTON BACKSCATTERED γ SOURCE DEVELOPMENT

γ BEAM: $E = 2.5 \text{ GeV}$
 $I = 0.5 \text{ A}$
 $N = 1.8 \cdot 10^{12}$

e^- BEAM: $E = 3 \text{ eV}$
 $P = 5 \text{ W}$
 $N = 3 \cdot 10^{11} \text{ Ph./wt.Vol.}$

γ BEAM: $E = 255 \text{ MeV}$
 $\Delta E = 2.7 \text{ MeV FOR ALL } E_\gamma$
 $I \approx 10^7/\text{SEC}$
 $P \approx 90\%$
 $\text{WITH } e^- \text{ TAGGING}$

NATIONAL SYNCHROTRON LIGHT SOURCE

POSSIBLE SPECIAL RADIATION
 SOURCE DISTRIBUTION

Fig. 14