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RESEARCH USING SYNCHROTRON RADIATION AT THE NATIONAL SYNCHROTRON LIGHT SOURCE*

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Summary

The National Synchrotron Light Source (NSLS) is now becoming operational with synchrotron radiation experiments beginning on the 700 MeV VUV electron storage ring. Commissioning of the 2.5 GeV x-ray storage ring has also begun with the experimental program expected to begin in 1983. The current status of the experimental program and instrumentation, and the plans for future developments, will be discussed. Although some early results have been obtained on VUV beam lines no attempt will be made in this paper to describe them. Instead, an overview of the beam line characteristics will be given, with an indication of those already operational. In the oral presentation some initial experimental results will be discussed.

Description of the NSLS

The NSLS consists of a 70 MeV linear accelerator, a 700 MeV booster synchrotron, a 700 MeV, 1 ampere, electron storage ring for VUV radiation, and a 2.5 GeV, 0.5 ampere electron storage ring for hard x-rays. The general facility plan is shown in Fig. 1 along with a number of lines tangent to the electron orbits at the bending magnets. These represent beam ports, each port capable of supporting up to 3 beam lines. On the x-ray ring, each port allows 50 mrad of horizontal radiation out of the vacuum chamber. When fully operational there will be about 50 beam lines on the ring. On the VUV ring, each port will allow 90 mrad of radiation out, serving a total of about 25 beam lines. Each ring can also support special insertion devices such as wigglers and undulators on the straight sections - 7 on the x-ray ring, and 2 on the VUV ring.

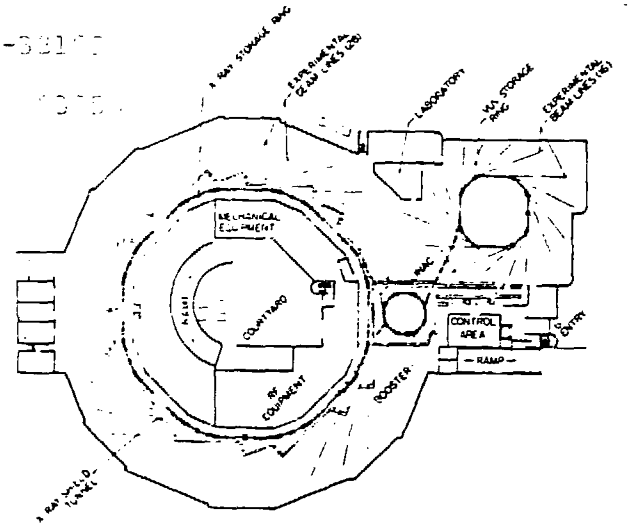

Fig. 1. Schematic of the NSLS facility showing the layout of the 70 MeV linac, the 700 MeV booster, the 700 MeV VUV storage ring, and the 2.5 GeV x-ray storage ring.

Beam lines at the NSLS have been specifically designed to utilize the high flux, high brightness radiation available. Figure 2 shows the flux integrated over all vertical angles for the x-ray and VUV arc magnet sources, and for the 6 T superconducting wiggler magnet on the x-ray ring. The critical wavelengths, source dimensions, and relevant time structures are listed in Table 1. The high flux and small source size (due to the low emittance design for the electron storage ring) gives the NSLS radiation a brightness greater than other currently operating storage rings.[1,2] For many experiments, such as small angle scattering and fluorescent microscopy the brightness is the true figure of merit.

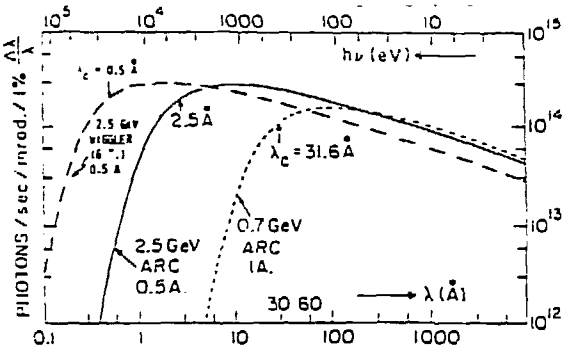

Fig. 2. Photon flux integrated over all vertical angles for the NSLS VUV and X-ray bending magnet sources and the 6 T superconducting wiggler on the x-ray ring. The total flux from the wiggler will be about six times that shown in the figure.

Table 1. NSLS EXPERIMENTAL PARAMETERS

	VUV (ARC)	X-Ray (Arc)	X-Ray (Wiggler)
Wavelength			
$[\lambda_c(\text{Å}); \epsilon_c(\text{keV})]$	[31;0.4]	[2.5;5.0]	[0.5;25.0]
Source Dimensions			
$2\sigma_y \times 2\sigma_x(\text{mm}^2)$	0.2x0.55	0.2x0.5	0.035x0.65
Vert.Angle $2\sigma'$(mrad)	1.4	0.4	0.3
Time Structure			
Number of Bunches	9	30	30
Orbital Time (nsec)	170	568	568
Bunch Length (nsec)	1.1	1.7	1.5

The experimental facilities at the NSLS are being constructed by the NSLS Division of Brookhaven National Laboratory and by Participating Research Teams. The beamlines built by the NSLS will be used entirely by general users; that is, anyone whose experiment has been approved by a proposal review committee. The Participating Research Teams (PRT) are comprised of groups of organizations and individuals who team up to design, construct, and operate a beam line. However, even on a PRT line the general user

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DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED will have about 25% access. The PRT arrangement has led to a great diversification in the types of beam lines being constructed, both in regard to the discipline of the research and the technical features of the instrumentation. At the present time, there are about 27 universities, 13 industrial firms, and 7 national laboratories actively involved in the development of PRT research programs. A feeling for the diversification of the facility can be gained by looking at Tables 2 and 3.

X-Ray Research

The critical energy of the x-ray photon spectrum from the bending magnets is 5 keV, giving a high usable flux up to about 22 keV. On all of the x-ray beam lines a thin Be window with a low energy cutoff of about 3 keV is used to separate the machine vacuum from atmosphere or from the optics. Thus, the working energy range for the bending magnet lines is between 3 and 22 keV. In order to extend the spectrum above 22 keV it is necessary to utilize the superconducting wiggler,[3] for which the critical wavelength $\lambda_c = 0.5$ Å ($E_c = 25$ keV). Usable flux should be available out to energies beyond 100 keV.

At the present time 15 beam ports are being instrumented on bending magnets and two ports for insertion devices. A total of 33 beam lines are under construction. These are listed in Table 2 along with the principle groups responsible for each beam line. Two general classes of beam lines are being developed - spectroscopy and scattering. The spectroscopy is primarily EXAFS (Extended X-ray Absorption Fine Structure) and is being carried out by biologists, chemists, metallurgists, and solid state physicists. The scattering beam lines are dedicated to chemical crystallography, small angle scattering, powder diffraction, and topography. The high brightness of the NSLS beams will allow anomalous dispersion and absorption edge characteristics to be fully utilized in experiments requiring high spatial resolution. The development of microprobe beam lines with high spatial resolution is possible.[4] It is the high brightness of the x-ray source at the NSLS which will allow a high photon flux to be focused onto the sample with good energy and momentum resolution.

At this conference, there will be detailed discussion of two beam lines by other authors. One, the NRL beamline,[5] is currently being constructed. The details of the type of optics which will be used on many NSLS beam lines can be found there, as well as in previously published material (see for example, references 6 and 7). The second one, the atomic physics beam line,[8] represents a beam line planned for the next phase of expansion of the NSLS facilities. Even though the x-ray ring is not quite ready for the initial experiments to begin, the facility and the scientific community are planning the future beam lines. Besides the atomic physics program, there will be the x-ray microprobe.[4] It will be used for trace element analysis by x-ray fluorescence, absorption, and computer tomographic techniques. With spatial resolution of 1 micron the technique will provide trace element determination in individual cells for biology and medicine.

Table 2. NSLS X-RAY BEAM LINES

X 9	Johnson Research Foundation	A.EXAFS (Biology) B.Scattering
X10	Exxon	A.Scattering B.EXAFS C.Crystallography
X11	N.C. State/Conn./BNL/ G.E/Argonne/Mobil/Dupont	EXAFS
X12	NSLS/BNL Biology	A.Small Angle Scattering B.Protein Crystallography
X13	NSLS/BNL Chemistry	A.Crystallography/Diffuse Scattering
	NSLS/BNL Physics/Penn/ SUNY/Allied Chemical	B.Energy Dispersive Diffraction
X14	ORNL	A.Diffuse Scattering B.Microprobe C.Topography
X15	Bell Labs	A.Scattering
X16	Bell Labs	B.Interferometry C.EXAFS/Scattering D.Spectroscopy
X17	Superconducting Wiggler	Spectroscopy/Scattering
X18	Purdue/W.Va./ Pitt./ Gulf/Ashland/UOP	A.Diffraction B.EXAFS
X19	NSLS NSLS/SUNY	A.EXAFS/SEXAFS/EPS B.Topography
X20	IBM/MIT	A.Scattering (High $\Delta Q/Q$) B.Scattering (Low $\Delta Q/Q$)
X21	SUNY	Scattering
X22	BNL Physics	A.Scattering (High $\Delta Q/Q$) B.Scattering ($\Delta E/E = 10^{-6}$)
X23	NRL/NBS	A.Topography
X24	NRL/NBS	B.SAXS C.EXAFS/SEXAFS D.Crystallography E.XPS/UPS
X25	Permanent Magnet Wiggler	Spectroscopy/Scattering

It is anticipated that three beam lines will be constructed on beam port X17 where the superconducting wiggler is being installed. The main branch will be a focused, monochromatic line instrumented for a general class of spectroscopy and scattering experiments which will take advantage of the flux enhancement, particularly at energies above 17 keV. There will be two beam lines utilizing horizontal scattering monochromators. One will be a fixed energy, focused, high flux line at an energy of 20 keV, for example. The second will be an unfocused line at 33 keV for medical imaging.

The high field wiggler will provide a high flux of photons up to about 100 keV, substantially higher than the energy of the photons from the bending magnets or permanent magnet devices. This energy range makes possible spectroscopy experiments on elements with absorption edges above Mo (20 keV). It also provides an intense beam of photons at several absorption edges useful in medical diagnostics, for example Iodine at 33.16 keV. Recent successful experiments[9] at the Stanford Synchrotron Radiation Laboratory have shown the potential of using synchrotron radiation for noninvasive aniography. Such a program in medical imaging will begin also at the NSLS.

During the next several years three or more insertion devices constructed of permanent magnets will be placed in straight sections of the x-ray ring. The principal feature shared by all these devices is an enhancement of the photon flux by a factor of 2N above the arc source flux. N is the number of periods of the magnetic field in the magnet. A permanent magnet wiggler will generally increase the flux over a broad spectrum of energies and will be ideal for spectroscopy experiments on dilute systems[10] gases, or two dimensional systems. One such magnet being constructed at the NSLS is a Vanadium-Permandur-Rare Earth Cobalt ($SmCo_5$) device with 12 periods. It will give a flux enhancement relative to the bending magnet flux of a factor of 24 for the wavelengths greater than 2 Å.

Another device, an undulator, enhances the flux at specific harmonic frequencies. Many possible designs are currently being studied for experimental programs at the NSLS.[11] One principal feature of these devices is that they can be designed to produce intense flux in a small horizontal opening angle, thus increasing the brightness of the source substantially. The peaking of the flux in a narrow energy range also decreases the amount of power incident on a monochromator, reducing the severe thermal problems expected, and making them ideal for high resolution scattering experiments. In fact, it seems reasonable to anticipate a beam port for scattering experiments where the peak in the flux is at about 4 keV. The very high fluxes will make possible experiments on two dimensional systems such as liquid crystals and adsorbed gases not possible with the flux from bending magnet sources. Another beam line could be constructed for doing high energy resolution inelastic scattering. The high flux and high brightness will compensate for the large loss in flux inherent in a normal incidence back scattering monochromator, and achieve a resolution of $\Delta E/E = 10^{-6}$.

A facility is also proposed to produce beams of monochromatic, linearly polarized photons with energies up to 500 MeV using laser light, Compton backscattered from the storage ring electron beams.[12] At moderate energies the decay modes of giant resonances could be studied and the high-momentum components of nuclear wavefunctions can be mapped out. The expected fluxes of polarized photons are comparable to or greater than the unpolarized flux in bremsstrahlung beams.

VUV Research

With a critical energy at 0.4 keV (31 Å), the 700 MeV VUV storage ring produces intense and very bright beams in the vacuum ultraviolet region of the electromagnetic spectrum. This ring is now in an early operational phase and some preliminary experiments are being performed. Overviews of the VUV beam lines and status reports have been published elsewhere.[13-15] Refering to Table 3, the single asterisks denote those beam lines now installed or being installed, while the double asterisks denote those beam lines which are operational and have taken some data. For several of the beam lines, in particular U4, U14, and U15, some data will be shown in the oral presentation. A quick count shows that as of November 1, 1982, 7 out of 13 are operational. The remainder will follow in only a few months.

Table 3. NSLS UV BEAM LINES

			λ(Å)	
U4	BELL LABS	**A.SEXAFS/ARUPS/XPS	12-1200	PGM
		*B.ARUPS	80-5000	TGM
		C.ARUPS/ABS	400-6000	NIM
U5	Free Electron Laser		2000-4000	
U6	IBM	* Lithography	White	
U7	BNL/SUNY/NSLS	**A.ARUPS/XPS/SEXAFS	15-1200	PGM
		B.ARUPS	80-2500	TGM
		C.Infrared	10^4-10^6	NIM
U8	IBM	*A.ARUPS	18-2000	TGM
		B.ARUPS	80-2500	TGM
		*C.EXAFS/SEXAFS/Microscopy	8-100	Fresnel Zone Plate
U9	NSLS/BNL-Chem.	**A.Fluorescence Lifetime	1050-120,000	NIM
	NSLS/BNL-Bio.	**B.Dichroism/Fluorescence	1200-300,000	NIM
U11	NSLS/BNL-Chem.	** Gas Phase Spectroscopy	300-2000	NIM
U12	PENN/ORNL/XEROX	*A.ARUPS	15-1200	TGM
		B.ARUPS	80-2500	TGM
		*C.Infrared	10^4-10^6	NIM
U14	NSLS	**A.ARUPS/XPS/SEXAFS	15-1200	PGM
U15	NSLS/SUNY	**Microscope	12-50	TGM

The beam lines on the VUV ring are primarily spectroscopy lines, dominated by ARUPS (Angle Resolved Photoemission Spectroscopy). Indeed, many of the beam lines will be doing basic surface science, complementary to LEED and Auger spectroscopy. However, there are several very important, exciting lines which do not involve photoemission. The lithography program (U6) may well lead to advanced techniques for production of microelectronics. The biology community, represented by the circular dichroism project, could very well see some progress in the understanding of DNA replication. One of the most exciting developments is perhaps the soft x-ray microscope (U15). Operating with a potential spacial resolution of 200 Å, it could use K edge absorption dual-energy imaging to map out the elemental distribution in live cells. The photon beam actually exits into the atmosphere through a pinhole, making live sample studies possible. It is not necessary to dry the samples or to use only thin sections. It will certainly be a complementary tool to the visible and electron microscopes.

The VUV ring has two straight sections which can be occupied by special sources. One of them is being used for the Free Electron Laser (FEL) experiment.[16] The undulator for this project is currently being installed. Combining the FEL concept with the properties of the high current stored beam (low beam emittance, small energy spread) should give a very high brightness, high flux source in the 2000-4000 Å region. Initially an external Argon 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 and the laser oscillating mode will be established. Comparing the output of the FEL with the undulator source, it is expected that there will be a gain of six orders of magnitude in the flux spectral density and in the source brightness.[10]

With operation of many beam lines commencing, the facility is looking ahead to enhancing its capabilities. Several groups are planning new beam lines. The NSLS division is studying the potential for a soft x-ray line in the 0.5–2 Å wavelength range. Consideration is also being given to such diverse programs as an infrared beam line[17] and x-ray holography.[18]

Conclusion

The NSLS is now beginning research in programs which touch all scientific disciplines. The diversity of programs, supported by universities, industrial labs, and national labs is unprecedented in a single facility. The excitement of beam line commissioning and the promises of the future developments give rise to a tremendous feeling of optimism concerning the scientific payback from the enormous efforts of so many people during the planning and construction phases of the facility. At the present rate of growth in numbers and types of beam lines, the NSLS must already look towards expansion to satisfy the demands of the scientific community.

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