Second National Conference on Synchrotron Radiation Instrumentation
July 15-17, 1981

CONF - 810750 - - 6

Progress and Prospects at the
National Synchrotron Light Source (NSLS)*

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July, 1981

MASTER**ABSTRACT**

This report discusses the NSLS project from inception until the present. The commencement and motivation for the program are considered from the viewpoint of the needs of various experiments and the concept of the 'Basic Source' is introduced. The Basic Source has high brightness and tunability within the ranges 0-0.3keV and 3-20keV. The inclusion of tunability implies the use of monochromators and the role of these is discussed. The Basic Source is important because it satisfies a very large proportion of users. The strategy of NSLS in providing a good Basic Source and special devices (monochromators and wigglers) to allow coverage of the energy ranges outside those of the Basic Source is described. The response of the NSLS to various other general and special needs of experimental users is described. Turning to the Free Electron Laser Project, a brief description of that device is given followed by a progress report of the overall NSLS construction program. The broad conclusion is that the NSLS facility will be completed within 2-3 months of its scheduled time scale and within its budget. This is considered to be a highly successful conclusion to the construction program.

*Work supported by the U.S. Department of Energy.

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by

Malcolm R. Howells

1. INTRODUCTION

In view of the impending completion of the NSLS project in October of this year and the initiation of the various research programs which will occur around that time, it is opportune to consider how the project began and how it acquired its present character. In this article, we consider the general scientific needs which created a demand for synchrotron radiation (SR) and review their influence on the design of the NSLS. We also identify a number of special needs of particular scientific experiments and evaluate the progress of the NSLS group in responding to these. Finally, we give a brief report on the construction installation and commissioning of the major components of the NSLS facility.

The idea of constructing a synchrotron light source at Brookhaven⁽¹⁾ arose in the early seventies. Its first public manifestation was in 1973 when a study symposium was held entitled "Research Applications of Synchrotron Radiation". This was stimulated by M. L. Perlman and R. E. Watson, who subsequently edited the proceedings⁽²⁾. Following the success of this event, a working group was formed under the leadership of M. Blume. The principal members of this were G. K. Green and R. Chasman, who worked on the photon and electron optics of the new machines, J. P. Blewett, who had been the first to observe SR experimentally⁽³⁾ and who edited the final proposal⁽⁴⁾ for the NSLS and J. B. Godel, who was responsible for the engineering of the new scheme.

In 1976 a special panel of the National Academy of Sciences had reported⁽⁵⁾ strongly in favour of expanding the U.S. capability in SR and so when the NSLS proposal was issued in February, 1977, it was received very sympathetically. In fact, funding was granted in October, 1977 and construction work began immediately. During the summer of that year, both Green and Chasman died tragically and Blewett had recently retired. Consequently a new management team was required. A. van Steenberg was appointed Project Head and has appointed as his immediate management group: M. Blume, J. B. Godel and K. Batchelor.

3. SCIENTIFIC NEEDS FOR SYNCHROTRON RADIATION

The successes of experimental scientists working with SR are now quite well documented. The special qualities of SR that are involved are variously characterized as intensity, collimation, small source size, polarization, vacuum cleanliness, spectral continuity, etc. Green and Chasman appreciated with special clarity that the first three of these are simply aspects of the single concept of 'brightness' and that source brightness is the parameter which determines the possible performance of optical instruments. It was clear that photon source brightness was directly determined by the product of the horizontal and vertical emittances of the electron beam and so Green and Chasman adopted as their primary aim the creation of storage rings of low emittance. This strategy has been continued by the present machine group.

The other salient feature of SR that appeals to almost all users is spectral continuity. SR is usually perceived as a tunable source of monochromatic radiation, thus implying that a monochromator must exist as part of the source. Historically, the photon wavelength ranges which have been available to SR researchers have been determined more by monochromator technology than anything else. The range 0-0.3keV is available at essentially all SR facilities because diffraction gratings work well in that range. Similarly, the range 3-20keV is routinely available at facilities with a high enough electron energy because crystals work well in that range. The decade 0.3-3keV is hardly used because neither gratings nor crystals are at their best.

Based on these ideas, we can define the 'Basic Source' comprising a source with high brightness and tunability within the ranges, 0-0.3 and 3-20keV. To evaluate how far this will satisfy the NSLS user community, we have prepared a Table^(I) of the experimental methods proposed by NSLS users with indications of their needs with regard to wavelength range and other special items. We may suppose that, being experiments announced for the start of a program, they will include the safer, more conventional methods with the more exotic or more speculative ones to follow later.

It is very striking how many users seem to be satisfied with the 'basic source' although we note significant interest in the ranges 0.3-3keV and >20keV. Space does not allow a full discussion of individual needs but we consider two types of need: general and specific. For the general we choose some examples and discuss the NSLS response with some brief indications of hardware designs. For the specific needs, we limit our discussion to tabulations intended to provide information in compressed form.

4. GENERAL NEEDS

We list in Table II a selection of general needs and the corresponding responses of the NSLS group. The main one, of course, is for the 'basic source' and to this we now turn.

4.1. The 'Basic Source'

It is now fairly well known that the NSLS will comprise two storage rings of energy 0.7GeV and 2.5GeV and an injection system consisting of a 0.07GeV linear accelerator and 0.7GeV booster synchrotron. These have been well documented^(8,9) elsewhere but we record the photon spectra (Fig. 1) and an overall layout (Fig. 2) of the facility. Tables III and IV give basic parameters of the two storage rings. A number of monochromators are to be provided giving tunability over various wavelength ranges. These are mostly custom built with particular needs in mind such as resolution, spectral purity, polarization and spatial and angular beam size. There is a considerable amount of material on record⁽¹⁰⁻¹³⁾ about these NSLS instruments.

4.2. Vacuum Protection

NSLS policy on vacuum questions has been defined⁽¹⁴⁾ fairly fully and naturally centers on the need for clean ultra-high vacuum (UHV) throughout all but the most special systems. Contamination of optical surfaces is considered an important problem and mass spectrometers are mandated for monitoring of organic contaminant levels. Most of the hardware needed for clean pumping systems, pressure and mass spectrum monitoring, etc., is available commercially, however, a suitable fast valve was considered important for protection against accidental rupture of the vacuum envelope and this was not available commercially. NSLS engineers have developed a fast valve⁽¹⁶⁾ which has clean all-metal construction, reasonable cost and a closing time of less than 5ms. The valve is shown in Fig. 3. Data on the conductance in the closed position, the method of recocking and other details are given in Reference 16.

4.3. Mirrors

It is generally accepted that one of the technical limitations to the exploitation of SR is the difficulty of manufacturing optical surfaces in the size, shape, accuracy, smoothness, materials, etc., which are required^(17,15). This limitation is compounded by the large number of mirrors that are needed and the budgetary constraints that exist.

Mirrors (Cont'd.)

The NSLS experimental group has responded to this by exploring as widely as possible within the optical manufacturing industry to find the limits of manufacturing capability and how to obtain the best quality components. These approaches have included many competitive bid solicitations. Both traditional fabrication methods and newer ones have been used. Among the latter are elastic bending and diamond turning plus post polishing. Diamond turning is especially attractive for quantity production and was used to make sets of paraboloidal mirrors (Fig. 4) for plane grating monochromators (see later). The success of this program is described in detail in Reference 18. The conclusion seems to be that we have obtained optics well within the surface figure specification that have a roughness (measured by visible light scattering) of $3.4 \pm 0.9\text{\AA}$ r.m.s. This is an exceptionally good result.

In order for the specifications of optics to be meaningful, it is necessary to have testing equipment capable of verifying compliance with the specifications. A testing laboratory has now been established at Brookhaven and some sample results are included in Reference 18.

Our general experiences in procuring optics may provide some useful guidance for others. Details relating to both gratings and mirrors are set out in an NSLS Technical Note⁽¹⁹⁾. We have also arranged a conference on this important subject to be held at Brookhaven in November, 1981⁽²⁰⁾.

4.4. Beam Stability

For many years, experience has been accumulating on the problems of using SR from electron beams which suffer from spatial and angular instabilities. These may be on timescales that vary from milliseconds to months. The conclusion is that extraordinary efforts are needed to eliminate the problem. At NSLS we have a good start by using dedicated storage rings. Various additional features have been built in to further improve the orbit stability. First, the magnet power supplies are monitored and controlled by microprocessors to a much higher accuracy than normal. Second, the problem of restoring the beam to its proper position is solved by software. Since a very large number of magnet parameters are involved in determining the position of the beam at any location, it is far beyond the ability of an operator to make corrections. The software controls all of the parameters and, it is hoped, will enable the beam position to be stabilized within tolerances which are small compared to the natural spatial and angular spread of the source.

4.5. Photon Energies Above 20KeV

The limitation here is the X-ray storage ring which has $E_c = 5\text{keV}$ so that 20keV is roughly the upper working limit. To extend this, a superconducting wiggler magnet development program⁽²²⁾ has been undertaken which is intended to deliver the first working prototype in time for the start-up of the X-ray storage ring.

The magnet has seven poles, the end two of which are excited at half current so as to produce zero net displacement of the beam. The design field is 6 Tesla, which will have the effect of shifting E_c up to about 25keV, thus allowing experimental work up to about 100keV. The overall layout is shown in Fig. 5, including the liquid nitrogen and liquid helium vessels.

The design of the poles and coils has already been tested. The prototype unit achieved a field of 5.8 Tesla at a current lower than the design current and after only 3 quenches. This was after some 'training' of the coils and showed that the training was being 'remembered' in the proper fashion.

4.6. The Intermediate Photon energy range 0.3 ~ 3.0keV

The difficulties of this photon energy range are such that no single method is likely to produce an intense, spectrally pure, high resolution, monochromatic beam. Using $4E_c$ as the maximum useful energy, it is possible to work up to 1.6keV on the VUV ring and this is probably the best approach for the range 0.3 - 1.6keV. For the range 1.6 - 3.0keV, the X-ray ring must be used.

Thus far we have used two approaches, both utilizing diffraction-grating instruments on the VUV ring. These are a plane grating grazing incidence monochromator^(12,13) (PGM), and a grazing incidence toroidal grating monochromator⁽²¹⁾ (TGM). The first operates in the range 0.01 - 0.8keV with good resolution ($<0.1\text{eV}$ over most of the range) and the second operates in the range 0.2 - 1.0keV with moderate resolution (1-2eV over most of the range). Three PGM's have been purchased by different groups. All have now been received and it is expected that they will be useful for solid state physics over most of their range. The TGM in existence at present is a modest device having no entrance slit or premirror and only one, rather small grating. However, in spite of this limited investment it is expected to be useful for experiments such as EXAFS and microscopy that do not require high resolution.

For the future, both the PGM and the TGM have built-in potential for 'stretching' to higher energy ranges and better resolution and no doubt this will be done. In addition, plans are presently under study for further schemes involving gratings or grating/crystal combinations which can cover the range not covered so far.

5. SPECIAL NEEDS

Space does not allow a detailed discussion of the needs of particular experiments. Table V does, however, contain a summary of some special needs that we are aware of and gives an indication of the extent to which the NSLS group has been able to act in response.

6. SPECIAL PROJECTS

A Free Electron Laser^(23,24) is under construction at the NSLS VUV ring and although it is not directed toward the production of light for experimental use, it contains a number of unique and exciting ingredients. The idea is based on the operation of an undulator⁽²⁵⁾. Fig. 6 shows the output spectrum of a particular undulator operating on the NSLS VUV ring. The spectrum is calculated for a finite collection area centered on the axis. One can see a first order peak at around 3500Å and then a series of higher order peaks of lower intensity at shorter wavelengths. In the rest frame of the electron, the undulator field appears like a travelling electromagnetic wave whose fundamental frequency is derived from the undulator period. The electron may scatter this wave producing a photon near to the forward direction in the laboratory frame as described by the spectrum in Fig. 6. If these photons are now returned back into the storage ring by mirrors in the manner of a gas laser, with the proper phase and timed to coincide with an electron bunch, then the probability of that bunch interacting with the undulator field will be enhanced and amplification can occur.

The experimental arrangement for doing this is shown in Fig. 7. The first form of the experiment which is planned to start on a similar time-scale to the other experiments will utilize an Argon laser to supply 3500Å light to determine the enhancement in the interaction with the undulator field or, in other words, to measure the gain of the laser.

7. PROGRESS REPORT

At the time of writing (July, 1981), the four-year construction program which began in October, 1978 has only two more months to run. Great progress has been made during this period and most of the major sub-systems of the NSLS are either complete or very nearly so. At the beginning of construction, a schedule was defined which essentially called for the NSLS to begin to operate, in the sense of being available to users, around October, 1981. The broad picture is that delays in various parts of the program, especially the building, have lead to a slippage of about 2-3 months in that schedule. In the opinion of this writer, this is a very minor delay and shows that the construction program to date has been highly successful. We now consider in more detail the progress to date in the individual components of the NSLS facility.

The building has been a source of both satisfaction, for its attractive appearance, and difficulty, for its imperfections and their effect on other parts of the schedule. A major difficulty, which is still not fully resolved at the time of writing, is the cooling system for both air and water. All the commissioning of magnets, r.f. systems, etc., carried out so far has utilized improvised cooling arrangements, however, the building has been fully occupied for approximately one year and the outstanding problems appear close to solution.

Of the accelerators, the linear accelerator has now been fully operational for approximately one year and injection into the booster synchrotron was achieved in March of this year. At present, the Linac/Booster combination is operated on a regular basis up to 400MeV energy and appears to operate reliably. All operational parameters are stored in computer files and by means of the computer, stable operation at 400 MeV is normally obtained in about 15 minutes from start-up. Operation at 700MeV will be achievable when installation of certain power supply components has been completed and no difficulty is expected with this.

The VUV ring (Fig. 8) has been assembled for more than a year and the magnet supplies, r.f. system, etc., have all been operated successfully. All of the beam line front ends have been partially installed (up to the UHV valve) and most of them have now been fully installed. The fast valves are an exception to this but they are expected to be available before research begins. Present commissioning efforts are directed toward operating the Booster/VUV ring transfer line. Extraction of a beam from the Booster has been successfully accomplished and injection into the VUV ring is obviously the next step.

PROGRESS REPORT (Cont'd.)

The X-ray storage ring (Fig. 9) is less advanced than the other machines. Considerable difficulties were experienced in closing the survey around the ring and this was not achieved until May of this year. Progress since then has been rapid, however, and all magnets are now in position as is the entire vacuum vessel. At the present time, the beam line front ends are being installed up as far as the UHV valve. Once this is completed, the next step will be vacuum integrity, which is expected some time in August. At about the same time, operation of the r.f. cavity into a dummy load and completion of the shield wall are intended.

The VUV experimental area is now ready for occupation and installation work has begun on a number of experimental beam lines. U14 (NSLS) and U4 (Bell Laboratories) are on the floor and under assembly now and several others, U7 (BNL Physics and Chemistry), U9 (NSLS, BNL Chemistry and Biology), U11 (NSLS, BNL Chemistry) and U15 (NSLS, SUNY Stony Brook) are also essentially ready. These latter are waiting in other buildings and installation work should begin during August.

8. CONCLUSION

As can be seen, progress to date has been very encouraging and the upcoming months promise to be very active ones. On the basis of present accomplishments and rate of progress, it appears that the VUV ring will be injected sometime during August and it is expected that the first photons will be admitted into a beam line by September 1st. The X-ray ring will be injected during September and an accelerated electron beam is expected to be achieved by October 1st. Since acceleration of the beam is required in the X-ray ring and not in the VUV, it is expected that the X-ray ring will require more prolonged commissioning studies. The X-ray experimental program therefore is estimated to start January 1, 1982.

If these projected milestones are indeed achieved as outlined above, then it will be a great credit to the individuals concerned at all levels of the NSLS organization and their reward will be the creation of a productive national facility and a successful user community. Perhaps it is appropriate to end by recording the highly significant fact that the NSLS construction project will be completed on budget!

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TABLE I

METHOD	BRIGHTNESS & TUNABILITY IN RANGE: 3-20 keV 0-0.3 keV	HIGHER ENERGIES >20 keV	DIFFICULT MIDDLE RANGE 0.3-3 keV	SPECIAL NEEDS
EXAFS	*	*		$\frac{\Delta E}{E} \sim 10^{-4}$ Mon'r.
SEXAFS	*		*	Monochromator Challenges
SAXS (Large Unit Cell, Biology)	*			Detector, Computer
Crystallography	*			Uniform Intensity 0.5mm^2
Anomalous Scattering	*	*		
Energy Dispersive Diffraction	*			
Diffuse Scattering	*			
Micro-Probe	*			10 μ Spot
Spectroscopy	*	*		
Topography	*			
Scattering	*			
XPS	*		*	
ARUPS	*		*	0.1 eV Resolution e^- Spectrometer
Lithography	*		*	Uniform Intensity Vacuum Problems
Infra-Red	*			Wide Vertical Aperture
Microscopy	*		*	Vacuum Problems
Optical Constants	*		*	
Circular Dichroism, MCD	*			Windows
Time Resolved Measurements	*			Suitable & Tunable Time Structure
Molecular Beam Chemistry	*			Flux, Spot Size
Very High Resolu- tion Work	*			

TABLE II

GENERAL NEEDS AND NSLS RESPONSES

The 'Basic Source' with high brightness and tunability in the ranges: 0-0.3 keV 3-20 keV	Two Storage Rings with the best possible brightness and the proper energy ranges. Monochromators to achieve tunability.
Vacuum Protection	Fast valve design and development.
Mirrors	Optical testing facility, special procurements involving diamond turning, November 1981 conference.
Beam Stability in position and direction.	Especially accurate power supply controls, software to control many parameters simultaneously to achieve corrections.
Intermediate energy Range 0.3 - 3 keV.	PGM and TGM Development (covers about 0.3 - 1.0 keV only).
High energy Range 20-100 keV.	Wiggler development.

TABLE III

VUV STORAGE RING PARAMETERS

Energy	0.7 GeV
Design Current	1 A ($\sim 10^{12}$ e ⁻)
λ_c (ϵ_c)	31.6Å (390 eV)
τ_{Touschek}	>3 hrs.
B (ρ)	1.2 T (1.91 m)
Circumference	51.0 m
τ_{ORB}	170.2 nsec
Lattice Structure	Separated function, 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)
Emittances	$\epsilon_x = 8.7 \times 10^{-8}$ rad.m $\epsilon_y = 8.8 \times 10^{-10}$ rad.m
Average Source Height (2σ)	0.2mm
Average Source Width (2σ)	0.7mm

TABLE IVX-RAY STORAGE RING PARAMETERS

Energy Range	2.5 GeV - 0.7 GeV
Design Current	1 A (2GeV) (3.9×10^{12} e ⁻) 0.5 A (2.5 GeV) (1.9×10^{12} e ⁻)
λ_c (eV)	2.48Å (5 keV)
τ_{Touschek} (2.5 GeV, 0.5A)	≥ 8 hrs.
B (ρ)	1.22 T (6.834 m)
Circumference	170.20 m
τ_{ORB}	567.7 nsec
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)
Emittances	$\epsilon_x = 8.1 \cdot 10^{-8}$ rad.m $\epsilon_y = 8.1 \times 10^{-10}$ rad.m
Average Source Height (2σ)	0.25mm
Average Source Width (2σ)	0.7mm

TABLE V

SPECIAL NEEDS AND RESPONSES

$\frac{\Delta E}{E} \sim 10^{-4}$ X-ray Monochromator for EXAFS	Design Study.
Detector and Data System for Fast SAXS.	Brookhaven Instrumentation Division Program.
10 μ Spot for Microprobe	---
Uniform intensity over 0.5mm ² for crystallography.	Sacrifice flux and use 'flat top' of Gaussian.
0.1 eV Resolution for ARUPS Range 0.3 - 3 keV.	PGM Plus 10° TGM 0-0.5keV, above 0.5keV -- nothing. Developed e ⁻ spectrometer with especially good angular rotation system.
Lithography: Uniform intensity over large area	IBM Group - Special Optics and Windows. BNL-Fast Valve(s).
Infra-Red: Large Vertical Aperture	Trials at low aperture first - special high vertical aperture vacuum vessel later.
Microscopy: Wavelength range and vacuum problems.	NSLS 2 1/2° TGM plus pinhole/window technology from SUNY, Stony Brook.
Circular Dichroism: Window Problems	Studies at SURF - no firm answer.
Time Resolved Work: Tunable Time Period.	Wobbler Development - in design study at present.
Molecular Beam Chemistry: High flux into small inter- action region.	Developed Special Wadsworth Mono- chromator with high aperture, low astigmatism.

Figure Captions

Fig. 1 - Photon output spectra for NSLS VUV and X-ray storage rings, the vertical arrows indicate λ_c values. The 0.5Å valve refers to the superconducting wiggler.

Fig. 2 - Building layout of NSLS Facility.

Fig. 3 - NSLS Fast Valve.

Fig. 4 - 4° grazing angle paraboloidal mirror for NSLS PGM.

Fig. 5 - Superconducting wiggler magnet for NSLS X-ray ring.

Fig. 6 - Spectrum of NSLS undulator on VUV ring. The parameters of the undulator are $K = 3.25$, $\gamma = 763$, $\gamma\theta = 0.267$ mr. K is the undulator parameter defined by the equation $K = (e/2\pi mc)\lambda_u B_{rms}$. λ_u is the undulator period and the other symbols have their usual meanings. γ is the electron energy in units of its rest energy. θ is the collection angle.

Fig. 7 - Layout of Free Electron Laser experiment.

Fig. 8 - NSLS VUV Storage ring before installation of shielding.

Fig. 9 - Installation of X-ray storage ring vacuum vessel.

SYNCHROTRON RADIATION SPECTRA FOR THE NSLS DESIGN PARAMETERS

Fig. 1

Fig. 2

Fig. 3

Fig. 4

NSLS SUPERCONDUCTING WIGGLER

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9