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proposal for a

NATIONAL SYNCHROTRON LIGHT SOURCE

MASTER

FEBRUARY 1977

BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

Volume I

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Proposal for a NATIONAL SYNCHROTRON LIGHT SOURCE

Edited by: JOHN P. BLEWETT

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PROPOSAL FOR A
NATIONAL SYNCHROTRON LIGHT SOURCE
AT THE
BROOKHAVEN NATIONAL LABORATORY

1. INTRODUCTION

1.1 Background and Summary

Since 1971 discussions have been held at Brookhaven National Laboratory on the desirability of construction of an electron synchrotron or storage ring which would be used exclusively for production of intense beams of photons with wavelengths in the ultraviolet and X-ray ranges. In September of 1972 a symposium was held with participants representing the various disciplines in which the radiation would be used. The proceedings of that symposium were published as BNL Report 50381. Since that date many more meetings have been held with interested potential users of the "dedicated" radiation source and a design of a possible storage ring system to supply all predicted needs has gradually evolved.

In 1975 a "Schedule 44" was submitted to the Division of Physical Research of the Energy Research and Development Administration requesting support for construction of a synchrotron radiation facility. A revised Schedule 44 for the project (now identified by the project number 78-CH-004) was submitted in May of 1976. It was supported by a "Conceptual Design Report" entitled "Synchrotron Radiation Research Facility" issued in June of 1976. The present proposal presents in more detail the machine, its characteristics and its expected uses.

Relativistic electrons travelling in a curved path in a magnetic field emit radiation covering a very broad spectrum and of very high intensity.

It will be assumed that the velocity of the electron differs negligibly from the velocity of light. Then the ratio γ of the electron's energy to its rest energy is given by

$$\gamma = 1957 E$$

where E is the electron energy in GeV. The radius ρ of the electron orbit in a magnetic field B is given (for ρ in meters and B in kilogauss) by

$$\begin{aligned} B\rho &= 33.35 E \\ &= 0.01704\gamma \end{aligned}$$

The emitted spectrum is most easily described in terms of a characteristic wavelength λ_c which, depending on how the spectrum is plotted, lies at or near the maximum of spectral intensity. For the purposes of this

section we mention only one type of plot. The number of photons emitted per fractional bandwidth $\Delta\lambda/\lambda$, per second, per milliampere, per milliradian of orbit is given by

$$N = (\Delta\lambda/\lambda) F_1 (\lambda/\lambda_c)$$

where F_1 is an integral of a Bessel function of fractional order. It is plotted in one of the graphs of the next section. For the present we mention the fact that its peak is at about $4\lambda_c$. The spectrum falls off rapidly on the short wavelength side of the maximum: for $\lambda = \text{about } \lambda_c/6$, F_1 has decreased by a factor of 100. On the long wavelength side the fall is more gradual: at $\lambda = 10,000 \lambda_c$, F_1 has decreased by only a factor of 10.

In Fig. 1-1 we present the spectra emitted by electrons of 400 MeV, 700 MeV, 1.5 GeV and 2.5 GeV moving through various sectors of the proposed storage rings.

The energy loss due to radiation is given by:

$$\delta E = 88.5 E^4 / \rho \text{ keV per revolution}$$

where, as before, E is in GeV and ρ is in meters. A 700-MeV electron in a field of 12 kilogauss will lose 11 keV per turn; a 2.5-GeV electron in the same field will lose almost 500 keV per turn. If a current of one ampere is circulating, the power loss at 700 MeV will be 11 kilowatts; at 2.5-GeV, about 500 kilowatts is converted to radiation. At higher fields or higher energies the energy loss is given by:

$$\delta E = 2.65 E^3 B \text{ keV per revolution.}$$

The radiation pattern is strongly peaked in the forward direction, coming off approximately tangentially to the curved electron orbit. The instantaneous radiation pattern from an electron is contained in a cone of approximately $1/\gamma$ radians half-width (γ is the electron energy in units of its rest energy). The radiation is strongly polarized, the degree of polarization varying with angle within the radiation cone.

In Section 2 of this Proposal the general properties of synchrotron radiation are presented in detail.

The scientific and technological need for a synchrotron radiation facility and some of the numerous applications of synchrotron radiation are discussed in Section 3.

A few of the characteristics of a synchrotron radiation source which are particularly advantageous are:

- intense radiation is available in spectral regions otherwise inaccessible.

1-3

FIGURE 1-1
Synchrotron radiation spectra for 400 and 700 MeV and 1.5 and 2.5 GeV electrons. On each spectrum the arrow indicates the critical wavelength λ_c .

- the spectrum is not marred by local peaks such as appear in the emission from gas discharges; hence, with monochromatization, a continuously tunable source is available.
- the radiation is polarized.
- the radiation is emitted from a "point source" of the order of 1 mm^3 in volume. This makes possible the use of refined optical systems which can accept only a small fraction of the radiation from conventional distributed sources.
- the radiation intensity is very stable (from a storage ring source).
- the intensity is very high. Intensities in the X-ray range can be several orders of magnitude higher than can be obtained from conventional X-ray tubes.

Major applications of synchrotron radiation are in solid state physics, chemistry, biology and in technology. Groups from academic and industrial research centers are making very active use of such synchrotron radiation sources as are now available, using the radiation in studies of absorption spectra, photoelectric emission, photochemistry, properties of free atoms and molecules, X-ray scattering and X-ray microscopy. New applications appear continually in areas as diverse as biochemistry, photometry, micro-lithography of integrated circuits and X-ray radiography.

No "dedicated" sources of synchrotron radiation with energies above 250 MeV exist in the United States. Parasitic operations have been carried on at the Cornell Electron Synchrotron, at the now dismantled Cambridge Electron Accelerator and at the Stanford Linear Accelerator Center's electron-positron ring (SPEAR). All of these machines were constructed for experiments in high energy physics and utilization of their output of synchrotron radiation has had second priority. Also, their designs were aimed at the high energy physics applications and were far from optimized as synchrotron radiation sources. But, now, the wide range and high value of research done with synchrotron radiation lends strong support to our proposal for construction of a national facility dedicated solely to the production of synchrotron radiation.

Section 4 of the Proposal is a description of the synchrotron radiation complex, which, as shown in Figs. 1-2 and 1-3 will include a 50-MeV linac, a 700-MeV injector synchrotron, a 700-MeV storage ring for photon production in the vacuum-ultraviolet (VUV) region, and a 2.5-GeV storage ring to provide

NATIONAL SYNCHROTRON LIGHT SOURCE
BROOKHAVEN NATIONAL LABORATORY

FIGURE 1-2

Plan of national synchrotron light source.

FIGURE 1-3

Artist's conception of national synchrotron light source.

photons in the far ultraviolet and hard X-ray ranges. The 700-MeV ring, planned to have fourfold symmetry will include four long straight sections for experimental applications and a number of beam ports distributed around the curved sectors of the ring. In the 2.5 GeV ring there will be six straight sections, some of which will be used for high-field "wigglers" - magnet arrays in which high fields cause sharp curvature in the orbit but restore the orbit to the equilibrium orbit with no net deflection; these will yield photon spectra with intensities usable to wavelengths as short as $0.2 \text{ \AA}$.

"Helical wigglers" can be installed in both rings. In these wigglers electrons move in a magnetic field whose direction rotates with distance along the axial orbit. Such an arrangement results in production of a spectrum much narrower than the ordinary synchrotron radiation spectrum. The properties of these devices, which have been studied in some detail at Brookhaven, are presented in Section 5 of this Proposal.

To house the three rings and the photon beam lines a "pre-engineered" structure will be erected, of a type widely used by Long Island industrial concerns. It will include an office and laboratory wing to house the machine operators and the visiting users. Buildings and utilities are described in Section 7.

The total cost of the facility is estimated to be \$24 million.

It includes:	Schedule A: Buildings and Utilities.....	\$4.040 million
	Schedule B: Storage Rings and Associated Equipment...	9.540
	Schedule C: E.D. and I.....	3.400
	Schedule D: Contingency.....	3.340
	Schedule E: Escalation.....	3.680

It is estimated that the facility can be completed in about three and a half years.

Details of the cost estimate and time and manpower schedules are given in Section 8.

Section 9 is an "environmental assessment" of the facility.

Pertinent reference material is included in Volume 2.

1.2 Design Choices

Two decisions have received a great deal of study.

The first relates to the possibility of a combined operation wherein only one storage ring could supply both the ultraviolet spectrum and

the hard X-rays. The 2.5 GeV ring straight sections could accommodate both the high field wigglers referred to above and low field wigglers with fields chosen to give a spectrum peaked at the desired ultraviolet wavelength. On the other hand, addition of a 700-MeV ring would virtually double the capability of the facility, leaving the high energy ring free for X-ray users and supplying a dedicated ultraviolet source for users of spectra in that range. A 700-MeV ring will cost about a third as much as the 2.5 GeV ring and will add about 10 percent to the cost of the whole facility. Hence, although combined operation in one ring appears perfectly feasible, it was decided that the facility should include two rings, one for production of X-rays and the other for ultraviolet users.

The second decision relates to the large ring; should it include four or six long straight sections? Originally both rings were designed with four-fold symmetry. When it was decided to include helical as well as conventional wigglers in this ring, the symmetry of the large ring was raised from four-fold to six-fold to supply more experimental space. This change increased the cost of the machine by about 5%. Since one straight section is required for injection, the change from four to six straight sections will almost double the usefulness of the facility.

1.3 Brookhaven as the Site

Brookhaven includes a unique assembly of capabilities which make it eminently qualified to undertake construction and management of a dedicated synchrotron radiation facility. Since its founding, nearly thirty years ago, Brookhaven has been a major accelerator center. Its staff has twice designed, constructed and operated accelerators with the world's highest energy. Alternating gradient ("strong") focussing was invented by a Brookhaven team; this technique has made it possible to construct accelerators, storage rings and beam transport systems that, formerly, were not feasible. The staff of Brookhaven's Accelerator Department (about 500 people) includes experts on all types of accelerators and storage rings. Part of the staff is engaged in operation of the 30-GeV proton synchrotron, another group is designing a 200-GeV colliding beam system (ISABELLE) and other groups are studying the designs of an intense neutron source for fusion studies and of the synchrotron radiation facility described in this Proposal.

It is, of course, intended that the synchrotron radiation laboratory be a national facility and that Brookhaven groups will use only a fraction

of its capabilities. There is, at Brookhaven, a great deal of experience in the operation of large research facilities, in their staffing by in-house research groups, and in their utilization by outside groups from university and industrial laboratories both from the United States and from elsewhere in the world. Among these facilities are the 30-GeV Alternating Gradient Synchrotron (AGS), the High Flux Beam Reactor (HFBR), and the Double Tandem Van de Graaff (TVDG). The HFBR is used in a variety of programs including Solid State Physics, Chemistry, Biology and Nuclear Physics. The in-house groups maintain the equipment (for example, spectrometers) in the course of carrying out their own research. Approximately 25% of the beam time involves research performed by outside groups or by outsiders in collaboration with Brookhaven personnel. At the TVDG the in-house groups use 50% of the beam time and 50% is set aside for use by outside researchers. At the AGS outside users account for a major fraction of the machine time. For both the AGS and the TVDG experimental time is assigned by a committee which considers the scientific value of the proposed experiment. No charge is made for beam time. In addition, the Laboratory supplies technical assistance and certain types of equipment for the experimenter. The Brookhaven housing facilities are made available to outside users. Brookhaven's programs have been widely praised by the user community. In general, the scientific productivity of both the in-house and the outside groups has been greatly enhanced by their interaction.

In addition to the special services related to the research facilities proper, the users have at their disposal a well-stocked Research Library, a central computer department, machine shops, photography, health physics and instrumentation divisions and all of the other normal ancillaries of a mature research center. During the summer, a large number of academic and industrial visitors join in the research programs and enjoy the adjacent seaside resort facilities.

We would expect the new synchrotron radiation laboratory to become a facility similar in operation to those already existing at Brookhaven. Programs and priorities would be established in close collaboration with the user community. Several meetings already have been held with groups of potential users; their guidance has been sought on all aspects of the machine design.

Brookhaven's location is particularly felicitous for a center for fundamental research. Its founders sought "a suitable location as close as

possible to Times Square"; this search resulted in the Long Island location midway along the densely inhabited northeast coast and easily accessible to all of the major northeastern universities and industrial laboratories. The Bell Laboratories in particular has expressed great interest in a possible Brookhaven synchrotron radiation facility. Many users from more distant locations and from abroad have been accommodated at Brookhaven and could, in the future, become users of the facility proposed here.

There is intense interest within Brookhaven in using synchrotron radiation for a variety of purposes. Particular interest is concentrated in Brookhaven's Chemistry Department and in the Solid State Division of the Physics Department. For some years a program has been in progress here of investigation of the properties of metals, insulators and superconductors, including studies of structure, radiation damage, optical absorption, thermal luminescence, internal friction and surface properties. In the Biology Department there is an active program of structural studies carried on by diffraction methods. A synchrotron radiation source will make possible extension of all of these studies into regions that, until now, have been inaccessible.

Both ultraviolet and X-radiation will find many uses in Brookhaven's applied programs and in energy-related projects. Surfaces of interest in absorption or conversion of solar energy can be studied and improved. Experiments on photosynthesis can be aided by the new sources of radiation. Extensive programs already in progress on metallurgy, superconducting materials, reactor materials and radiation damage all will find uses for the new radiation source.

1.4 Synchrotron Radiation - A Brief History

The fact that electrons, when accelerated, radiate electromagnetic waves has been appreciated for some time (cf. H. Hertz, Ann. Phys. Chem., 36, 1 (1889)). Shortly after Einstein proposed his theory of relativity Schott and others investigated the radiative behavior of relativistic electrons and accurate analyses are firmly presented in the standard texts (e.g., Page and Adams, "Electrodynamics" Van Nostrand, 1940).

As electron energies in accelerators began to penetrate the relativistic range, energy losses due to radiation began to worry accelerator designers. The first publication on this question was by Iwanenko and Pomeranchuk (D. Iwanenko and I. Pomeranchuk, Phys. Rev. 65, 343 (1944)) who

presented a formula for energy loss due to radiation and suggested that radiation might set an upper limit to energy achievable in the betatron, or as it was often called in those days the "induction electron accelerator". This idea was picked up by J. P. Blewett, then at the General Electric Company and J. Schwinger who was still at the M.I.T. Radiation Laboratory. Blewett's paper (J.P. Blewett, Phys. Rev. 69, 87, 1946) gave the derivation of Iwanenko and Pomeranchuk's formula, discussed the effect of other electrons on single electron radiation and described an experiment on the G.E. 100-MeV betatron that correlated the observed shrinking of the electron orbit with the predicted radiation loss. Schwinger (J.S. Schwinger, Phys. Rev. 70, 798, 1946 and 75, 1912, 1949) provided an analysis of the radiation spectrum to be expected.

The radiation was not seen in the 100 MeV G.E. machine for the simple reason that its vacuum chamber was opaque. The first visual observation was in 1947 (F.R. Elder, A.M. Gurewitsch, R.V. Langmuir and H.C. Pollock, Phys. Rev. 71, 829, 1947), also at the General Electric Research Laboratory in Schenectady where, on the new 75 MeV electron synchrotron, its operators observed a brilliant light emitted tangent to the circular orbit of the electron beam. This was the radiation predicted by Iwanenko and Pomeranchuk, Blewett and Schwinger. Its total energy and spectrum were as predicted; later it was observed and measured in many laboratories.

Initially the new radiation was regarded primarily as a nuisance - a natural phenomenon whose primary consequence was the limitation on energy to which electrons could be accelerated. It had extreme effects on the high energy physics program - the future of electron synchrotrons was circumscribed and the only high energy alternative proved to be the linear accelerator - hence SLAC.

The next significant event in the history of synchrotron radiation occurred at Cornell where the group in charge of the 300-MeV electron synchrotron found it interesting to observe and check against the theory the energy and spectral distribution of synchrotron radiation. Tombouliau and Hartman's paper "Spectral and Angular Distribution of Ultraviolet Radiation from the 300-MeV Cornell Synchrotron" (D.H. Tombouliau and P.L. Hartman, Phys. Rev. 102, 1423, 1956) is still an indispensable reference in the field.

Tombouliau's interests turned to applying synchrotron radiation for spectroscopic purposes and at the Cambridge Electron Accelerator (CEA) he started work which was cut short by his untimely death. It was only in the early 1970's, shortly before CEA was to be shut down, that synchrotron radiation research was revived at this facility.

The first sustained research program employing synchrotron radiation was initiated in 1961 when an ultraviolet radiation port was placed on the 180 MeV synchrotron at the National Bureau of Standards. To this day, Madden and his associates have employed this facility, primarily for atomic and molecular spectroscopy. By the mid 60's, light was also being utilized at the higher energy synchrotrons at Frascati, Italy, at Hamburg and in Tokyo. Though emitting harder radiation than the NBS machine, these too, were being primarily used for spectroscopic purposes. In the early 60's a consortium of midwestern universities endeavored to put together a high energy facility. While this did not come to be, one by-product was the 240-MeV storage ring at the University of Wisconsin. This has become an important national facility for synchrotron radiation research; its energy limits it to spectroscopic studies.

Structural studies employing synchrotron radiation have awaited the 1970's. Deserving of mention is the European Molecular Biology Organization (EMBO) whose investigations have pioneered with low angle diffraction studies of muscle functions at Hamburg. The British effort at Daresbury has seen considerable activity in x-ray topography while workers at SPEAR, the high energy storage ring at Stanford, have developed x-ray absorption edge spectroscopy into a valuable tool for probing local atomic structure.

At this date there are over twenty machines throughout the world where synchrotron radiation is being utilized. About half of the machines are synchrotrons, the others being storage rings, and, in all but a few cases, the radiation is being obtained parasitically at a high energy physics facility. In the United States there are four extant facilities: NBS, Cornell, Wisconsin and Stanford. The NBS machine has been converted into a storage ring, rated at 180 MeV though it has recently operated at 12 mA and 243 MeV. Several faculty members have used hard x-rays taken out through a Be window during high energy runs on the 12 GeV Cornell synchrotron. There are national users' facilities being operated at

Wisconsin and Stanford. Wisconsin is a dedicated operation providing ultra-violet radiation while x-rays are obtained parasitically at Stanford - there are occasional shifts when SPEAR is turned on specifically for the synchrotron light users.

The leading synchrotron light sources are listed in Table 1.1.

Research utilizing synchrotron light is an explosively growing field as evidenced either by the numbers of research publications or by the diversity of applications. The emission of synchrotron light may still be a nuisance to the designer of high energy machines but it has become important in its own right - important enough that storage rings are now being designed and built to be light sources. One person's trouble is another's treasure.

TABLE 1.1

Synchrotron Radiation Sources

Location	Name	Type (Synchrotron or Storage Ring)	Energy (GeV)	Circulating Current (mA)	Status (Operating Construction or Proposed)
U.S.					
NBS, Washington	SURF I	Synch	0.18	5	Op.
Madison, Wisc.	TANTALUS I	S.R.	0.24	40	Op.
Stanford, Cal.	SPEAR	S.R.	4.2	70	Op.
Cornell		Synch	12	2	Op.
BNL	NSLS	S.R.	2	1000	Prop
			0.7	1000	Prop
Madison, Wisc.	TANTALUS II	S.R.	2.5	1000	Prop
			0.75	1000	Prop
U.K.					
Daresbury	NINA	Synch	5.0	60	Op.
Daresbury	SRS	S.R.	2.0	1000	Prop
France					
Orsay	ACO	S.R.	0.54	35	Op.
Orsay	DCI	S.R.	1.8	400	Constr
Germany					
Bonn		Synch	2.5	20	Op.
Hamburg	DESY	Synch	7.5	80	Op.
Hamburg	DORIS	S.R.	3.5	900	Op.
Italy					
Frascati		Synch	1.1	100	Op.
Frascati	ADONE	S.R.	1.5	60	Op.
Sweden					
Lund		Synch	1.2	40	Op.
U.S.S.R.					
Novosibirsk	VEPP 2	Synch	0.7		Op.
Novosibirsk	VEPP 3	S.R.	3.5	500	Constr
Moscow	FIAN	Synch	0.7		Prop
Moscow	RAKNVA	S.R.	1.3		Constr
Yerevan		Synch	6.1	22	Op.
Japan					
Tokyo	INS-SOR	Synch	1.3	60	Op.
Tokyo	SOR-RING	S.R.	0.3	100	Op.

2. CHARACTERISTICS OF SYNCHROTRON RADIATION

2.1 Introduction

The literature includes treatment of the basic features of synchrotron radiation and many reviews. Most of the published data is specific to the rings used as examples. Important characteristics have been collected in parametric form by G. K. Green in his report "Spectra and Optics of Synchrotron Radiation". This paper is included in Volume II of this Proposal. In this section we present a brief summary of the report and use the methods developed to estimate the characteristics of the storage ring sources.

2.2 Synchrotron Radiation Spectra

The energy of a particle can be stated in electron volts or as γ , the ratio of its mass to its rest mass. When a charged particle is accelerated it radiates, but the radiation per particle is very weak unless γ is large ($\gamma \gg 100$). Acceleration in the direction of motion by attainable electric fields produces radiation which is almost unmeasurably small, however, transverse acceleration by readily available magnetic fields will produce copious radiation at large γ . A particle having charge e and bent by a magnetic field on a circular path of radius ρ will radiate energy per turn

$$\delta E = 4\pi e^2 \gamma^4 / 3\rho.$$

Of the two most convenient particles, the proton with rest mass 938 MeV is not very useful because a γ of 1000 would require an energy of about 1 TeV. The electron has the same unit charge but a rest mass of only 0.511 MeV and will reach a γ of 1000 at an energy of 511 MeV, a range easily obtainable in a storage ring. If we express the energy of the electron in GeV and its radius in meters, the radiation energy per turn is

$$\delta E = 88.5 E^4 / \rho \text{ keV/turn} \quad (2-1)$$

or, since $B\rho = 33.35 E$ with B in kilogauss, and $\gamma = 1957E$

$$\delta E = 2.65 E^3 B \text{ keV/turn} \quad (2-2)$$

It follows directly that the power radiated by electron current I amperes in an electron storage ring of energy E is

$$P = 88.5 I E^4 / \rho = 2.65 E^3 I B \text{ kW}, \quad (2-3)$$

and must be supplied by the ring's accelerating system.

Spectral characteristics of the radiation depend only on the energy and radius of curvature of the electron. Both spectral and angular functions are best described in terms of a characteristic wavelength

$$\lambda_c = 4\pi\rho/3\gamma^3 \quad (2-4)$$

and since $\gamma = 1957 \text{ E(GeV)}$ and $B\rho(\text{kilogauss-m}) = 33.35 \text{ E(GeV)}$ we can express λ_c in practical units,

$$\lambda_c = 5.59 \rho/E^3 = 186/BE^2 \text{ angstroms} \quad (2-5)$$

($\epsilon = h\nu = 12,400/\lambda \text{ ev for } \lambda \text{ in } \text{\AA}$)

The radiated power as a function of wavelength λ is

$$P = 5.95 \times 10^{-11} (\gamma^4/\rho) G_2 \text{ ergs per (1\% bandwidth, sec, mamp, mrad of orbit arc)} \quad (2-6)$$

in which G_2 is a Bessel function integral which is a function only of the ratio λ/λ_c . G_2 is plotted in Fig. 2-1 versus λ/λ_c . The peak of this power spectrum is at a λ about $2/3$ of λ_c and the power falls off rapidly at longer and shorter wavelengths. As λ_c is shifted upward or downward by changing E and ρ the shape of the spectrum, expressed in terms of λ/λ_c , does not change but the power varies as $(\text{energy})^4/\text{radius}$. The power spectrum can alternatively be shown as the integral of power at all wavelengths greater than λ with λ expressed by the ratio λ/λ_c . In Fig. 2-2 it will be seen that half of the radiated power is emitted above λ_c ; 4% above $10 \lambda_c$ and only 0.2% above $100 \lambda_c$. Only 2% of the power is emitted below $\lambda_c/5$.

The radiation is emitted almost tangentially to the orbit and so appears as a flat sheet subtending the 2π of orbital bend angle θ . As a function of angle Ψ , normal to the orbital plane, the power falls off rapidly.

$$P = (\gamma^5/\rho) F_7(\gamma\Psi) \text{ watts per (mamp, mrad } \theta, \text{ mrad } \Psi) \quad (2-7)$$

with F_7 a polynomial in $\gamma\Psi$. Figure 2-3 shows F_7 as a function of $\gamma\Psi$ in radians. The specific power (per unit solid angle) varies as $(\text{energy})^5/\text{radius}$ while the angle is inversely proportional to electron energy since, as γ increases, Ψ diminishes.

For most purposes the flux in photons per second is wanted, rather than power. If the functions of Fig. 2-1 are divided by photon energy $h\nu$ the result is flux integrated over all Ψ

$$N(1\%) = \gamma F(1\%, \lambda/\lambda_c) \text{ photons per (1\% bandwidth sec, mamp, mrad of orbit arc)} \quad (2-8)$$

with F plotted in Fig. 2-4. The total flux of photons diminishes only about 3 times from λ_c to $1000 \lambda_c$, but falls two orders of magnitude from λ_c to $0.16 \lambda_c$. The flux is proportional to energy, to number of ma of beam and to number of mrad of arc; λ_c varies with energy and radius of curvature (Eq. 2-5).

FIGURE 2-1

$$G_2 = (\lambda_c/\lambda)^2 \int_{\lambda_c/\lambda}^{\infty} K_{5/3}(\eta) d\eta.$$

FIGURE 2-2

Percent of radiated power at all wavelengths greater than λ , vs λ/λ_c .

FIGURE 2-3

Power vs angle ψ . See Eq. 2-7.

FIGURE 2-4

Photon flux vs λ/λ_c . See Eq. 2-8.

The radiation is strongly polarized. In the plane of the orbit it is completely polarized with the electric vector parallel to the orbital plane. At angle ψ to the orbital plane the radiation is elliptically polarized. Angular distribution of the parallel and perpendicular components of polarization are shown in Fig. 2-5 as a percentage of $N(\lambda/\lambda_c, 0)$, the flux per unit ψ at $\psi = 0$. At any wavelength λ the shape of the angular distributions and the degree of polarization depend only on λ/λ_c . The angular scale (in radians) is $1/\gamma$.

The flux to which the curves of Fig. 2-5 are normalized, $N(\lambda/\lambda_c, 0)$, is a function of γ and of expressions involving modified Bessel functions of λ/λ_c ,

$$N(\lambda/\lambda_c, 0) = \gamma^2 F(1\%, \lambda/\lambda_c, 0) \text{ photons per } \begin{matrix} (1\% \text{ bandwidth, sec} \\ \text{mamp, mrad of orbit} \\ \text{arc, mrad } \psi) \end{matrix} \quad (2-9)$$

Flux per unit vertical angle ψ (Fig. 2-6) falls more rapidly than total flux (Fig. 2-4) toward longer wavelengths because the angular spread increases at the longer wavelengths. The flux per unit vertical angle, at a given λ/λ_c , varies as $(\text{energy})^2$.

2.3 The Electron Beam Shape

The relationships of the previous section apply to an electron beam of infinitesimal cross section and angular divergence. Although the cross section and divergence of the beam in an electron storage ring are small, their finite size has an important effect on the optical characteristics of the source. An alternating gradient ring has the inherent property of varying beam size, modulated by the magnet lattice. Beam size in the elements of a sector of the lattice of Fig. 4-1 is shown in Fig. 2-7. The beam size is composed of two normal distributions; one is produced by the rapid transverse betatron oscillations in the radial and vertical directions, and the other by the slow radial momentum oscillations. The betatron oscillations produce a distribution of the beam electrons in both position and angle. Distributions at selected azimuthal points of the lattice of Fig. 4-1 and Fig. 2-7 are shown in Fig. 2-8 as phase space plots in position y and angle y' for the vertical space and corresponding x and x' for the horizontal space. Each ellipse is the 2σ contour of the electron beam at the indicated azimuth. Although the focussing structure of the ring modifies the shape and inclination of the phase space contours, the area is an invariant - the emittance. Oscillatory motions are damped by the radiation until they reach a lower limit set by the quantum fluctuations. The vertical emittance

FIGURE 2-5

Relative polarization normalized to flux at $\Psi = 0$,
for range of values of λ/λ_c .

FIGURE 2-6

Photon flux per unit vertical angle Ψ vs λ/λ_c . See Eq. 2-9.

FIGURE 2-7
Electron beam size in the center of the magnet units of Fig. 4-1.

FIGURE 2-8

Electron beam 2σ contours in y, y' and x, x' phase space.

would be extremely small if it were not increased by energy coupled from the horizontal oscillations. The example assumes 10% vertical-horizontal coupling, a magnitude attainable in practice.

Beam size is given by the projection of the contours on the y and x axes and is a minimum in the center of the insertion which is arranged to be a double focus. Momentum oscillations produce a distribution of orbits proportional to the momentum function x_p (Fig. 4-2) and this distribution increases the x beam size where x_p is large. In the example of Fig. 2-8 the horizontal sizes in BB and in the insertion are increased very little by momentum spread, but the size in BB1 is approximately doubled.

2.4 The Synchrotron Radiation Source

When an electron radiates, the photons originate from its instantaneous position, but are distributed in angle about the electron direction. This angular distribution is a function only of the γ of the electron and of the ratio of the observed wavelength, λ , to the characteristic wavelength, λ_c (Fig. 2-5). An approximation of the angular variance σ_r of the radiation distribution is given by

$$\begin{aligned}\gamma\sigma_r &= 0.57 (\lambda/\lambda_c)^{0.43} \text{ radians} \\ \sigma_r &= 1.66 \times 10^{-2} \gamma^{0.28} (\lambda/\rho)^{0.43} \text{ mrad}\end{aligned}\tag{2-10}$$

and so for γ of order thousands the angles are very small, even at relatively long wavelengths. Approximate radiation angle σ_r for selected energies in the storage rings is shown as a function of λ in Fig. 2-9.

If we consider the radiation from a short segment of arc the source size distribution will appear the same as the electron beam size distribution. The source angular distribution will be a composite of the angular variance of the electron beam σ_b' , and the radiation angular variance, σ_r . The source angular variance is then

$$\sqrt{\sigma_b'^2 + \sigma_r^2}$$

A synchrotron light source will subtend an orbit arc $\pm\theta$ and at radius of curvature ρ will be of finite length $\pm s = \pm\rho\theta$. In order to synthesize an equivalent optical source, project all elements of the source length onto the transverse plane at the center. Projection of the radial, or x, coordinate of the central orbit is shown in Fig. 2-10a. In order to synthesize an equivalent optical source project all elements of the source length onto the transverse phase plane, x-x', at the center. Fig. 2-10b is a diagram of this optical source

FIGURE 2-9

Photon radiation angle σ vs λ at different energies and radii of curvature.

a

b

FIGURE 2-10

Planar optical source in the x, x' phase space.

phase space configuration. Ellipses of the radiation from source elements at the center and ends are shown superimposed on the source band. Source width will be $\pm\sigma_x$, the width of the electron beam and will be approximately constant if the source is not too long. The angular extent $\pm x'$, will be determined by the acceptance of the limiting optical elements. Very long sources will have position displaced as a function of angle by the sagitta $\rho x'^2/2$. The photon density (photons per $dx dx'$) as a function of x will be approximately constant with x' .

In the vertical, or y , direction the center of the source has phase space contour σ_y by $\sigma_{y'} = (\sigma_y^2 + \sigma_r^2)^{1/2}$; Fig. 2-11a. The upstream end of the source will project onto the plane at the center with the radiation contour axis rotated, due to the angular spread, Fig 2-11b. Similarly the downstream end of the source will project back as in 2-11c. When all elements of the finite source are added the apparent source has unaltered angular distribution but the height y is increased, 2-11d. If $\sigma_r s / \sigma_y$ is not more than one this source height increase is small but at $\sigma_r s / \sigma_y$ about 4 the source height is doubled.

In Fig. 2-12 a synthesized source is shown in the two phase planes y, y' and x, x' . A ray at y, y' in the source will strike a plane at distance ℓ at $y + y'\ell, y'$. As the radiation propagates the contours in the phase planes rotate with angles preserved (in the absence of focussing) and with size increasing. An aperture is indicated in the x, x' plane. This aperture, projected back on the source, determines the angular acceptance of orbital arc, $\pm x'$ or $\pm\theta$.

Photon density in the phase planes, e.g. photons per $dx dx'$ and photons per $dy dy'$ is an invariant if there is no x - y optical coupling. The brightness of the image, photons per unit area-unit solid angle, cannot exceed the brightness of the source (it is invariably less due to losses) even though the shape of the image can be altered by the optics. Consequently, for critical experiments it is important that the source be bright. If the storage ring emittance is small the electron beam divergence, σ_x, σ_y , will be small compared to the radiation divergence, σ_r , even though the beam be focussed to a small size, σ_x, σ_y . If the source length, $\pm s$, is also such that $\sigma_r s / \sigma_y < 1$ we can obtain relatively simple approximations for the parallel polarized photon distribution in the source. Integrate over all x ; the axial photon distributions in y and y' are (omitting numerical factors for simplicity)

FIGURE 2-11
Planar optical source in y, y' phase space.

FIGURE 2-12
Optical source propagating along axis l .

$$dN(y)/dy \sim \frac{\gamma^2 H_2}{\rho} \frac{\sigma_r s}{\sigma_y} e^{-(y^2/2\sigma_y^2)} \quad (2-11)$$

$$dN(y')/dy' \sim \frac{\gamma^2 H_2 s}{\rho} e^{-(y'^2/2\sigma_r^2)} \quad (2-12)$$

and integrating over all y

$$dN(x)/dx \sim \frac{\gamma f G_1}{\sigma_x} e^{-(x^2/2\sigma_x^2)} \quad (2-13)$$

$$dN(x')/dx' \sim \gamma f G_1 \quad (2-14)$$

The central phase space density, at (0,0) is

$$d^2N/dydy' \sim \frac{\gamma^2 H_2 s}{\rho \sigma_y} \quad (2-15)$$

$$d^2N/dxdx' \sim \frac{\gamma f G_1}{\sigma_x} \quad (2-16)$$

Spectral functions f, G_1 , H_2 , and $\gamma\sigma$ of (λ/λ_c) are slowly varying, see Fig. 2-13.

2.5 Choice of Source Parameters

The basic parameters of a storage ring are energy and radius of curvature. Magnetic field is fixed by $B(\text{kgauss}) = 33.35 E/\rho$ and the characteristic wavelength by

$$\lambda_c = 186/BE^2 = 5.59\rho/E^3$$

Flux falls off rapidly below λ_c (Figs. 2-4, 2-6)

<u>Relative Flux</u>		
<u>λ</u>	<u>Total Photons</u>	<u>Photons/unit Ψ</u>
λ_c	1	1
$\lambda_c/2$	0.45	0.66
$\lambda_c/3$	0.17	0.35
$\lambda_c/4$	0.08	0.18
$\lambda_c/5$	0.04	0.09

X-ray experiments often need wavelengths in the neighborhood of $1\text{\AA}$ (12,400 eV) and sometimes at a small fraction of an angstrom. Since non-focussing crystal monochromators have an angular acceptance, rather than total flux acceptance,

FIGURE 2-13
Spectra parameters vs λ/λ_c .

they can be used down to perhaps $\lambda_c/5$ where the flux per unit angle has dropped an order of magnitude. At $\lambda_c/10$ the flux per unit angle decreases an additional two orders of magnitude and is in general unusable.

The multiplier on the flux per unit angle function of Fig. 2-6 is γ^2 ($3.83 \times 10^6 E^2$) and on the total flux function of Fig. 2-4 is γ (1957E). Consideration by experimenters in the field indicates that, for X-ray work, λ_c should be of the order of $1\text{\AA}$. Consequently, the energy of the electrons should be high. However, the power radiated and required to be supplied by the rf system, in addition to cavity losses, is

$$P = 88.5 E^4 / \rho \text{ kw/amp}$$

and the power density of the radiation at one meter from a source is approximately

$$P/A = 1.4 E^5 / \rho \text{ kw/cm}^2 \text{ amp}$$

This rapid increase of power with energy indicates that the energy should be no greater than necessary. A resolution of these contradictory energy requirements is provided by the use of short sectors of strong magnetic field, called 'wigglers', to supply several stations from bright, short wavelength sources

<u>Power</u>						
<u>E</u>	<u>ρ</u>	<u>B</u>	<u>λ_c</u>	<u>P in arcs</u>	<u>P/wiggler</u>	<u>P/A at 1 m</u>
GeV	m	kgauss	$\text{\AA}$	kw/amp	kw/amp, 16°	kw/cm ² , amp
2	8.17	8.16	5.71	173		5.5
2.5	8.17	10.2	2.92	423		16.7
2	1.67	40	1.16		38	27
2.5	2.08	40	0.74		74	66
4.58	12.7	12.0	0.74	3066		222
4.96	16.2	10.2	0.74	3306		259

In the foregoing table the first two entries are for a ring with bending radius of about 8 m. At 2.5 GeV the λ_c of the radiation from the bending magnets is about $3\text{\AA}$, and will give usable flux down to about $\lambda_c/5$ or $0.6\text{\AA}$ (20 keV). The next two entries apply to wigglers in insertions of the 2.5 GeV ring. At 40 kilogauss, a conservative field strength for superconductors, the λ_c would be $1.16\text{\AA}$ at 2 GeV and $0.74\text{\AA}$ at 2.5 GeV. Usable flux could be obtained down to some $0.15\text{\AA}$ (80 keV). Power per wiggler of total bend 16° (-4° , 8° , -4°) per amp of beam is tabulated. It seems desirable to set the upper energy of the ring at 2.5 GeV and to provide rf power for 1 amp of beam at 2 GeV and for $1/2$

amp at 2.5 GeV. Simultaneous operation of four wigglers at these conditions would then require total rf power of 325 kW and 360 kW respectively.

If a λ_c of 0.74 Å were to be produced in the arc magnets, without wigglers, typical examples are given in the last two table entries. Since flux at a given λ_c is proportional to γ , and flux per unit vertical angle to γ^2 , the higher energy rings could be operated at 1/2 or 1/4 the current. The available rf power would still need to be some 800 kW and the ring circumference would be about twice that of the lower energy rings. It does not seem warranted to double the cost of the ring to reduce λ_c in the bending magnets when a brighter corresponding source can be had in the wigglers.

The VUV spans, somewhat arbitrarily, 25 - 1000 Å (500 - 12 eV). The 2.5 GeV ring will emit flux throughout this region (Figs. 1-1 and 2-4). For the λ_c of the arc magnets, 2.9 Å, some 56% of the photons lie at wavelengths greater than 25 Å, but 95% of the power is radiated below 25 Å. Comparable VUV flux can be produced by a lower energy ring as illustrated in the following table.

Comparison of Flux and Power

<u>E</u>	<u>I</u>	<u>ρ</u>	<u>λ_c</u>	<u>P</u>	<u>P/A at 1 m</u>	<u>Photons/1%, sec, mrad</u>		
GeV	amp	m	Å	w/50mrad	w/cm ²	25 Å	50 Å	500 Å
2.5	1/2	8.17	2.9	1700	8300	2.6×10^{14}	2.3×10^{14}	1.2×10^{14}
0.7	1	1.92	31	88	123	9.6×10^{13}	1.4×10^{14}	1.3×10^{14}

The 0.7 GeV ring with 2 m radius of curvature can have a first optical element as close as 1.5 m from the source. A 7-1/2 cm element can gather 50 mrad (horizontal) of flux and is readily cooled. Optical elements to gather the same VUV flux from the 2.5 GeV ring would be at least 2-3 times as large and would have difficult cooling problems. Since vertical angular distribution is a function of λ/λ_c as well as γ (Eq. 2-10), the vertical radiation angles at VUV wavelengths are not much greater from the 0.7 GeV than from the 2.5 GeV ring. The percent parallel polarization is a function only of λ/λ_c , and is therefore greater in the VUV from the 0.7 GeV ring than from the higher energy ring. Representative values are tabulated as follows:

Vertical Radiation Distribution and % Parallel Polarization

	<u>σ (mrad)</u>			<u>f (%)</u>		
	$\lambda = 25 \text{ \AA}$	$50 \text{ \AA}$	$500 \text{ \AA}$	$25 \text{ \AA}$	$50 \text{ \AA}$	$500 \text{ \AA}$
2.5 GeV	0.3	0.4	1.0	$79\frac{1}{2}$	78	$75\frac{1}{2}$
0.7 GeV	0.4	0.5	1.4	89	$85\frac{1}{2}$	78

The advantages of the lower energy ring for VUV are then copious flux, highly polarized, but with reasonable radiation power density and close approach to the source. Short source distances together with much less shielding for the lower energy permit simpler and less expensive instrumentation of the beam lines. The 0.7 GeV ring would use the common injector for loading large circulating currents and would permit independent scheduling of the X-ray and VUV research programs.

Geometric and optical properties of the source are a sensitive function of the choice of magnet lattice of the storage ring; use of alternating-gradient focussing provides a wide range of choice. The considerations of Sect. 2.4 show that a good optical source wants small beam size, e.g. small σ_x and σ_y . However, for high brightness the electron beam divergence, σ'_x and σ'_y must be only a fraction of the radiation divergence, and for both size and divergence to be small the emittance must be small.

Small emittance is one of the most important properties of a good storage ring source. It is obtained by making the ν , or natural transverse oscillation frequency, high and by applying strong momentum compaction which means a small X_p function. The lattice designs presented in Section 4 have small emittance and strong momentum compaction in order to produce small sources in the bending magnets, including the momentum dispersion of the horizontal size. Momentum function, X_p , is made approximately zero in the insertions and a double focus at the insertion center is done by the triplet lenses. The resulting sources produced by a transverse wiggler are very small and very bright (Fig. 2-8). Since X_p is very small and amplitude function, β , is small at the wiggler, its short sectors of strong magnetic field will have little effect on the damping of the rings.

Electron beam 1σ size and angular distributions have been calculated from the quantum fluctuations with 10% coupling assumed. Imperfections and instabilities will increase these sizes by probability functions which can be estimated. After adjustments and refinements during a running-in period the actual beam sizes should be within a factor of $\sqrt{2}$ to 2 times the sizes calculated for an ideal ring. In the following table, sizes are given for three different source locations in the arc bending magnets and for the center of the insertion where a wiggler would be placed.

	<u>1σ Source Amplitude</u>			
	Vertical		Horizontal	
	<u>y</u>	<u>y'</u>	<u>x</u>	<u>x'</u>
2.5 GeV arc magnet	0.07 mm	0.02 mrad	0.32 mm	0.22 mrad
	0.027	0.022	0.81	0.69
	0.042	0.022	0.42	0.44
2.5 GeV insertion	0.009	0.034	0.15	0.20
700 MeV arc magnet	0.064	0.027	0.25	0.34
	0.05	0.027	0.18	0.28
	0.035	0.027	0.25	0.26
700 MeV insertion	0.006	0.065	0.15	0.26

Radiation angular σ_r is plotted in Fig. 2-9, and is larger than σ_y . If the source length, s , is such that $\sigma_r s / \sigma_y = \sigma \rho \theta / \sigma_y < 1$ the central vertical phase space density can be approximated by Eq. (2-15) and is proportional to s . To the short source approximation of this section, and with $\sigma_x < \sigma_r$, the central brightness is given by

$$d^4N/dxdx'dydy' = 3.5 \times 10^7 \gamma^2 H_2 / 2\pi \sigma_x \sigma_y \quad (2.17)$$

photons per sec, amp, 1% bandwidth, $\text{mm}^2 \text{mrad}^2$ with σ_x and σ_y in mm. The central brightness in the short source approximation is not a function of source length.

The vertical phase space density, $d^2N/dydy'$, in photons per sec, amp, mrad θ , mm-mrad and central brightness in photons per sec, amp, $\text{mm}^2\text{-mrad}^2$ are tabulated for the arc bending magnet and wiggler sources at λ_c and for 1% bandwidth:

	<u>Phase Space Density at y=0</u>	<u>Brightness at x=y=0</u>
2.5 GeV arc magnet	1.3×10^{16}	8×10^{15}
	3.6×10^{16}	9×10^{15}
	2.2×10^{16}	1.1×10^{16}
2.5 GeV insertion	1.1×10^{17}	1.4×10^{17}
700 MeV arc magnet	1.2×10^{15}	9×10^{14}
	1.5×10^{15}	1.7×10^{15}
	2.1×10^{15}	1.7×10^{15}
700 MeV insertion	1.2×10^{16}	1.7×10^{16}

In summary, we conclude that a facility to serve a national community of synchrotron radiation users should include: a high brightness 2.5 GeV storage ring for X-rays with insertions designed for wigglers; a 700 MeV storage ring for VUV; and, a booster injector designed to fill both rings to currents approaching one ampere.

3. SCIENTIFIC JUSTIFICATION FOR A SYNCHROTRON RADIATION FACILITY

3.1 Introduction

The interaction of radiation with matter, one of the most important of physical phenomena, has unique applications in essentially all fields of science. To exploit such applications, a great variety of radiation sources has been developed during the past century. These cover much of the spectrum, from the visible at wavelengths of several thousand angstrom, through the "vacuum ultraviolet" (VUV), and into the hard x-ray range at less than 1 angstrom. Most of these sources, however, suffer from one or another disadvantage - low intensity, poor stability, strong concentration at specific wavelengths; and, for some spectral ranges, there are no satisfactory sources. Hence, the advent of synchrotron radiation has been received with considerable enthusiasm. Its unique combination of characteristics - a continuous spectrum, high intensity, polarization, and high temporal and spatial stability - make it a truly versatile tool in the exploration of the properties of matter.

At the 2.5-GeV ring the spectrum of the radiation emitted by the circulating electron beam as it traverses the bending magnets will have its peak at about $3 \text{ \AA}$; and the spectrum emerging from a 40 kG wiggler will be peaked below $1 \text{ \AA}$. Thus useful radiation derivable from this ring will extend from about $0.3 \text{ \AA}$ through the x-ray range, into the ultraviolet, and beyond. The 700-MeV ring will provide a spectrum peaked at about $30 \text{ \AA}$ and extending over the whole ultraviolet range.

Summaries of the many applications of synchrotron radiation will be found in the following references:

"Research Applications of Synchrotron Radiation - Proceedings of a Study-Symposium held at Brookhaven National Laboratory", BNL 50381, June 1973.

"Synchrotron Radiation - Light Fantastic", M. L. Perlman, E. M. Rowe and R. E. Watson, Physics Today, Vol. 27, 7, 30 (1974).

"The Scientific Case for Research with Synchrotron Radiation", Daresbury Report DL/SRF/R3, 1975.

"Synchrotron Radiation Research", K. O. Hodgson, H. Winick and G. Chu, Editors. Stanford Synchrotron Radiation Project Report 76/100, 1976.

In this section we present briefly a few of the areas in which synchrotron radiation has proved to be a powerful tool. There are two headings:

ultraviolet and x-ray applications. The section will close with a statement on the relationship of this class of research to energy technology.

3.2 Ultraviolet Applications

Synchrotron radiation has been used most extensively for investigations in the ultraviolet; the availability to experimenters of beams at shorter wavelengths has been comparatively limited. Many kinds of measurements have been made on all classes of substances and systems, but the framework of the research may perhaps be encompassed briefly. With optical and photoelectron emission methods, the structure and behavior of solids and surfaces have been studied. The ground and excited states of simple inorganic gases and of their ions and the properties of excited states in more complex organic molecules have been investigated, largely by optical techniques. All of these studies, which originate from the interaction between light and the electronic charge, are directed to improving the understanding of how electrons behave in these matter systems. This understanding is basic to a large number of more obvious, important phenomena: chemical reactions in the various parts of the atmosphere; the functioning of pure metals, alloys, semiconductors and superconductors in their manifold applications; the performance of surfaces in catalyzing chemical reactions; and the transfer of excitation between molecules that is at the heart of biological processes. A few typical UV investigations are:

3.2.1 Solids and surfaces:

An early example of this work, carried out by D. Eastman and his associates at Tantalus I, is an investigation of the conduction band states of gold.¹ From photoelectron spectra measured at a series of discrete wavelengths ranging from about 100 to 1000 Å, it was possible to make deductions about the ordinarily unoccupied states above the Fermi level in the band. In an extension of this kind of study, J. E. Rowe took advantage not only of the high-intensity continuous spectrum required for the gold work but also of the polarization properties of synchrotron radiation. From photoemission measurements at several wavelengths and by changing the angle between polarization direction and crystal axis (Fig. 3-1), Rowe was able to show² that the band structure calculations for the semiconductor GaSe are incorrect and require reconsideration. At LURE near Paris, optical reflectivity methods have been employed to study energy levels and symmetries in the band structures of a number of transition metal dichalcogenides³; continuous photon energy variation and photon polarization

FIGURE 3-1

Photoelectron spectra from GaSe (001) taken at three photon energies and with polarization directions parallel and perpendicular to a crystal plane. The abscissa scale is the initial electron energy state referenced to the Fermi level as zero.

are needed for such experiments. These interesting layered compounds have been the subject of study also by angle-resolved photoemission, in experiments carried out at Tantalus I.⁴

Such investigations are naturally related to valence and conduction electron band studies designed to obtain information about chemical bonding between adsorbed molecules and the surfaces of noble and transition metals, such as those used in catalysts. T. Gustafsson and co-workers reported observations made at Tantalus I of photoemission spectra taken at several wavelengths of CO covered surfaces of Ni and Pd. By comparison of these spectra with those of gaseous CO, they were able to deduce which of the CO gas levels are involved in the bonding and how these levels are perturbed.⁵ It may be noted that the conclusions rest in part on the results of similar studies with hydrocarbons adsorbed on Ni and W, under conditions in which these molecules do not bond appreciably. Apai and colleagues, at Stanford SSRP have similarly investigated CO on Pt in order to ascertain effects of the chemisorbed molecules on the metal valence levels.⁶ Information even about the orientation of the CO molecule on the metal surface has been obtained from photoemission.⁷ This directional result requires direction sensitive experiments, and it is the angular and polarization variation of the photoelectron spectra which are crucial.

Data for such simple adsorbates as CO are interesting in themselves and they must be well understood if one is to progress to more complex substrate-adsorbate systems.

3.2.2 Atomic and molecular phenomena:

The relatively small effort thus far devoted by chemists and physicists to the study of atoms and molecules with synchrotron radiation has yielded results which have interested many researchers in application of this radiation to their work.

On the fundamental level of details of electronic structure and behavior in isolated atoms, a group working at LURE has measured, as a function of wavelength, the relative probability of single to double photoionization of the rare gases. These experiments require a light beam which is intense, monochromatic, variable in energy, and highly collimated; ergo synchrotron radiation. The results show that electron correlation effects must be taken into account,

not only insofar as they describe the initial state of the atom, but also as they influence the Auger process and internal inelastic processes which may accompany it.⁸ At the National Bureau of Standards the characteristics of identified individual states resulting from laser light excitation have been probed by utilization of synchrotron radiation to scan the absorption spectra of the excited species. Recently, L. C. Lee⁹ has reported measurements made at Tantalus I on highly excited Rydberg states in the molecules CH_4 , CF_4 , CF_3Cl , and SF_6 . These states lie above the dissociation and ionization energies and are of obvious interest in connection with the possible reactions of these molecules in the upper atmosphere. At LURE, the fluorescent, or radiation emitting, deexcitation of states in such ions as N_2^+ , CO^+ , and N_2O^+ is being investigated. Certain CO^+ states are found not to fluoresce; they probably dissociate. The development of high resolution monochromators at LURE has made it possible to take advantage of the intense, collimated radiation to produce for study of deexcitation nearly single rotational states in a vibronic molecular level. By coupling mass spectrometry with these techniques, the fragmentation behavior of such highly excited states in C_2H_4 , O_2 and CO_2 is being investigated,¹⁰ and it is easy to see that the study of chemical reactions of these states is not far in the offing.

Details of the much weaker bonding responsible for the formation of such clustering molecules as $(\text{H}_2\text{O})_n$, $(\text{CH}_3\text{OH})_n$, and $(\text{CO}_2)_n$ have been explored by Taylor and Jones¹¹ at Tantalus I. Clusters of this kind, which are produced at very low states of excitation by expansion of vapor through a high velocity nozzle beam, are intermediate between the isolated molecule and the condensed phase; and their dissociation energetics are being studied by photoionization mass spectrometry with monochromatized synchrotron radiation.

Transfer of electronic excitation in more complex molecular systems has been investigated in a number of experiments done by Lopez-Delgado and associates at Stanford and at LURE. An especially interesting behavior is shown by a singlet excited state of tetracene, which at room temperature can fission into two triplet excitons. This fission, an internal transfer, results in the attenuation of fluorescence associated with direct singlet deexcitation. Decay of this fluorescence, which has been measured with the singlet state laser produced, is not well understood, probably because of secondary non-linear excitation intensity effects. The Stanford results (Fig. 3-2) show that most of the

Figure 3-2. Tetracene single crystal fluorescence decay. Counts in the photon detector are plotted versus a time scaled abscissa. Circles show the detector response to the Stanford SSRP light pulse at 4080 Å which was used to excite the tetracene state. Triangles show detector response to the tetracene fluorescence at 5000 Å. Deconvolution of the excitation shape from the observed fluorescence curve yields the lifetimes quoted in the text.

decay is by a process with 0.20 nanosecond lifetime, and about 10% is via a longer period of 1.7 nanosecond.¹² Temperature effects on lifetimes and branchings are yet to be explored.

At LURE transfer of excitation from states in benzene to aniline has been studied in the gas through observation of the decrease in benzene fluorescence intensity and increase in aniline fluorescence as the aniline concentration is raised. It happens that the states thus produced in the aniline are found to differ from those resulting from direct photoexcitation.

Energy transfer in biologically interesting larger molecules has also been attacked by fluorescence methods; Alpert and Delgado have begun to examine the tryptophane-haeme system. It has been known for some time that the fluorescent decay of an excited state in tryptophane is strongly quenched when haemoglobins are present. The new LURE measurements¹³ show that, although the fluorescence intensity may be decreased 100-fold in the presence of haeme, the fluorescence decay lifetime is shortened only about 20%. This probably means that there exists a tryptophane-haeme energy transferring conformation whose lifetime is long relative to the fluorescence time.

References

1. D. E. Eastman and W. D. Grobman, Phys. Rev. Lett. 28, 1327 (1972).
2. J. E. Rowe, Polarized Light Photoemission Spectroscopy: Symmetry Properties of Surface Electronic Wave Functions; Notes on Users Group Conference 1975 Phys. Sci. Lab. Univ. of Wisc., Stoughton, p. 28.
3. R. Mamy, B. Thieblemont, and O. Cerclier, Reflectivité des Dichalcogenures Lamellaires de Metaux de Transition; Progress Report July 1975-June 1976, L.U.R.E., Univ. of Paris, Orsay, p. 40.
4. V. V. Smith, P. K. Larsen, and S. Chiang, Angle-Resolved Photoemission from Layered Compounds and Surfaces; reported at Users Group Conference 1976, Phys. Sci. Lab., Univ. of Wisc., Stoughton.
5. T. Gustafsson, E. W. Plummer, D. E. Eastman, and J. L. Freeouf, Solid State Commun. 17, 391 (1975); also J. W. Davenport, T. Gustafsson, and E. W. Plummer, $h\nu$ -Dependent Partial Photoionization Cross Sections and their Importance; Notes on Users Group Conference 1975, Phys. Sci. Lab., Univ. of Wisc., Stoughton, p. 33.
6. G. Apai, P. S. Wehner, J. Stöhr, R. S. Williams, and D. A. Shirley, Lawrence Berkeley Laboratory Report, LBL-5122 (1976), unpublished.

7. E. W. Plummer, private communication.
8. V. Schmidt, N. Sandner, H. Kuntzmüller, F. Willeumier, P. Dhez, and E. Kallne, Etude des Processus d'Ionization Double dans les Couches Externes des Atomes par Spectroscopic Ionique, Progress Report July 1975-June 1976, L.U.R.E., Univ. of Paris, Orsay, p. 12.
9. L. C. Lee, Observations of Rydberg States of CH₄, CF₄, SF₆, and CF₃CL in λ 550-680 Å; reported at Users Group Conference 1976, Phys. Sci. Lab., Univ. of Wisc., Stoughton.
10. P. M. Guyon, I. Nenner, N. Moulin, R. Botter, J. Eland, and A. Tabshe', Progress Report July 1975-June 1976, L.U.R.E., Univ. of Paris, Orsay p. 25.
11. J. W. Taylor and G. G. Jones, Cluster Reactions and Photoionization Mass Spectrometry; Notes on Users Group Conference 1975, Phys. Sci. Lab., Univ. of Wisc., Stoughton, p. 34.
12. R. López-Delgado, J. A. Miehe', and B. Sipp, Stanford Synchrotron Radiation Project Report SSRP 76/04 (1976), unpublished.
13. B. Alpert and R. López-Delgado, Progress Report July 1975-June-1976, L.U.R.E. Univ. of Paris, Orsay, p. 63.

3.3 X-Ray Applications

3.3.1 Photoabsorption:

One of the most notable examples of the impact of synchrotron radiation on basic and applied science has been x-ray photoabsorption. It has been recognized since the 1920's that structure, such as that displayed in Fig. 3-3, exists above x-ray absorption edges and that this structure is associated with the absorbing atom's local environment. However, it remained for the advent of synchrotron light to make this a broadly useful source of information; a continuum light source is required and the limitations of bremsstrahlung from an x-ray tube make the experiments tedious and pretty well limit them to concentrated systems. Synchrotron light provides a $10^5 - 10^6$ increase in photon flux over the x-ray tube. This can be translated into faster data rates, increased resolution, and operation with systems of absorbing species as dilute as ten parts per million. There are presented unique opportunities to study chemically active sites in biomolecules, as well as thin films, dissolved species, amorphous solids and catalysts. Consider catalysts for example; it is possible to monitor the platinum particles in a working fuel cell or catalytic reaction system in such a way as to observe the degradation of the active sites.

The fine structure in the spectrum of Fig. 3-3 appears because the photoelectron originating at the absorbing atom is backscattered by the neighboring atoms. This modulates the electron wave function amplitude at the origin and hence the strength of photoabsorption. While theoretical problems still remain, it is generally possible to determine near neighbor radial distances to an accuracy of $0.1 \text{ \AA}$; and when scattering is dominated by one shell of heavier near neighbors, that distance may be good to $\pm 0.01 \text{ \AA}$. Additional information is available in the spectrum; the position of the edge is indicative of the chemical state of the absorber atom, and structure at and below the edge, associated with bound final states, can indicate the symmetry of the site. Spectra of this type have been measured in absorption or in fluorescence, the latter providing higher sensitivity for very dilute systems; the method is highly surface sensitive if either the ejected photoelectrons or Auger electrons, which have short escape distances, are employed as a monitor of the absorption.

The absorption fine structure technique is particularly useful for disordered or dilute systems since the structure in these is difficult to

3-10

FIGURE 3-3

The L_1 , L_2 and L_3 x-ray absorption edges of gold metal. The plot shows the absorption of x-rays by gold metal as a function of the energy of the x-rays. The structure seen above each absorption edge is associated with the environment a gold atom finds itself in and provides a measure of the number and distance of near neighboring atoms (from D. Sayers, unpublished).

ascertain by diffraction methods. Semiconductors have been studied in the crystalline and amorphous forms and it has been possible to relate models of the amorphous structure with the absorption spectra.¹ While the above-mentioned study of catalysts is exciting, one of the currently most lively applications of x-ray absorption spectroscopy is to active metal sites in biologically functioning molecules under physiological conditions. The local environment of the Fe site in several forms of hemoglobin² has been studied with the object of correlating with it the variation in oxygen affinity, a property essential to the oxygenation of blood. Rubredoxin, an electron transfer enzyme of molecular weight about 6000; which is related to enzymes involved in pathways of respiration, photosynthesis, nitrogen fixation, etc. has also been a recent object of study.³ Around the Fe site in rubredoxin four sulfur atoms are tetrahedrally coordinated, and preliminary x-ray crystallographic results had indicated that one sulfur lay anomalously close to the iron site. X-ray absorption spectroscopy, however, showed that all Fe-S distances are normal and subsequently, a new analysis of crystallographic data at higher resolution proved to be in accord with this. Absorption spectra of rubredoxin provided evidence that in its reduced form the Fe-S distance is $0.05 \text{ \AA}$ greater than in the oxidized form; this finding is an example of the microscopic chemical detail which can be revealed.

Some other biologically important systems which have been examined are the environs of the Mn believed important to photosynthesis in leaf chloroplasts⁴ and the Mo sites in the enzyme nitrogenase, important for nitrogen fixation in nature.⁵ Attempts to obtain this enzyme of molecular weight about a quarter million, in the form of crystals suitable for diffraction studies have not succeeded. The hope is that by discovering the structural changes associated with the nitrogen fixing, x-ray absorption will help yield an overall understanding of the process. This, then, might allow modeling of the process in a non-biological, potentially industrially practicable way. The other investigations mentioned were also not limited to crystalline samples: the rubredoxin was studied both as a crystal and in solutions where its biological integrity is greater; the Fe-S distances proved to be the same to $\pm 0.02 \text{ \AA}$. A leaf plucked from a tree outside the laboratory was used as such to obtain the spectrum of Mn in chloroplasts.

Dilute atom constituents are, of course, important in other cases. They may be involved in physiological function and malfunction, such as the calcium ion is in muscle. They are found in air and water pollutants, and with information about the chemical forms of such species, obtainable from x-ray absorption fine structure, one is aided in determining the mechanisms for their dispersal. These properties of alloys and insulators important to technological application are often dependent on small amounts of impurities.

Thin samples, also, may be investigated. For example, a set of superconducting thin films of Al₅ compounds was studied at Bell Laboratories and the local order observed was correlated with superconducting transition temperatures.

The linear polarization of synchrotron light is, on occasion, an advantage; it imposes a preferential direction on emission of the photoelectron. The absorption spectrum is an anisotropic probe if, to illustrate the extreme case, the environment around all absorbing atoms has the same orientation, as it might in a crystalline sample. There is the opportunity here to ascertain displacement correlation functions associated with lattice vibrations and lattice distortions.

3.3.2 Diffraction:

X-ray diffraction, the time-honored standard approach to structure, also gains from the employment of synchrotron radiation. Its use for the analysis of biological structures was pioneered by Holmes and his associates of the Max Planck Institute in Heidelberg. The development of specialized facilities for biological work at DESY and Stanford has been slow but is now approaching a point where a wide variety of investigation is permitted. The two classes of experiment of greatest interest to the biologist are crystallography and low angle scattering. These two and diffuse x-ray scattering and x-ray topography are useful as well to the materials scientist and all four classes are considered in the following paragraphs.

A frequently troublesome problem in the crystallography of structures with large unit cells, such as biomolecules, has been the fixing of the phases of the atomic scattering. This has been attacked by comparison of patterns obtained with different characteristic x-ray lines or by heavy metal

isomorphous substitution. With synchrotron light one may select the x-ray wavelength so as to optimize the anomalous scattering that occurs at the absorption edge of a constituent atomic species of the crystal. This tuning enhancement of that particular species' contribution to the scattering⁶ makes it more readily evident in an electron density plot, and the large difference in scattering observed between diffraction patterns taken at wavelengths at both sides of the absorption edge provides an extra tool for phase determination when other means, such as isomorphous substitution, are difficult or not possible. Our understanding of the anomalous scattering relies at present on imperfect theory. The intensity and continuum character of synchrotron light make it particularly suited to experimental studies of this scattering. There is interesting basic physics in anomalous scattering; the ability to understand quantitatively its contributions to a given diffraction pattern would serve to improve the spatial information which can be inferred from that pattern, whether obtained with synchrotron light or with an x-ray tube.

Many substances of biological interest have not been subjected to structural investigation because they are not obtainable as crystals of the size required for conventional crystallography. Synchrotron light, with the small source size we propose here, may make it feasible to solve structures using crystals even as small as fifty microns across. This will significantly increase the number of substances accessible to investigation. Even when sample size is not a problem, the brightness of the photon source makes for higher resolution and shorter exposure times. In a variant of conventional diffraction, for which synchrotron radiation is especially suited, the x-ray continuum is incident on the specimen and an energy-sensitive device is used to detect the scattering at a fixed angle; this variant shows promise⁷ for its simplicity and speed. There are also prospects for optical holographic reconstruction⁸ of crystallographic data.

Brightness and x-ray wavelength tunability greatly facilitate low angle diffraction studies of the organization, over tens and hundreds of angstroms of muscle and retina, of fibers and lamellar systems, of macromolecules in solution, and of dense multiphase systems such as porous catalysts. Using position-sensitive area detectors Hendricks, at Oak Ridge, is studying radiation induced voids in solids with an x-ray tube. Synchrotron light should let this class of study be extended. In recent studies⁹ of insect muscle function there is evidence that ATP at low concentrations produces a

distinct state intermediate between rigor and relaxation which is not simply a mixture of these two. Biological membranes and their states in the presence of various divalent cations (e.g. Ca^{2+} or Zn^{2+}) are of practical interest. One can observe the anomalous scattering near the K edge of the particular metal cation, whose location was being sought. X-ray absorption spectroscopy may be used in conjunction with low angle scattering for such a study.

The gains to be had from the use of synchrotron radiation in conventional or low angle diffraction sometimes are great enough to allow dynamic studies on biologically or physically meaningful time scales to be made. In general, this requires line or area position sensitive detectors. Preliminary work on muscle function has already been done in Europe and studies of the kinetics of enzymes and other biomolecules will be attempted in the near future. Questions of conformational changes, side chain vibrations, substrate binding, diffusion, etc. will be addressed. Diffraction techniques can be coupled to timed stimuli such as temperature or pH jumps, chemical or light activation.

For structural determinations in systems as simple as rock salt, synchrotron radiation is certainly not required; however, there exist, in addition to biomolecules, other large unit cell systems for the study of which it is advantageous. More important, probably are the possibilities for dynamic studies of crystal phase transitions, of diffusion, and of solid state reactions. Synchrotron radiation allows use of long wavelengths permitting investigation of large complexes, even subcellular structures, bridging the gap between conventional x-ray and electron microscopy.

In addition to the sharp Bragg peaks resulting from regular ordering in crystals, diffuse x-ray scattering occurs if there are density fluctuations. In contrast to x-ray absorption spectroscopy, which gives information primarily about the first one or two shells of nearest neighbors, diffuse scattering is a measure of the number and kinds of atomic pairs out to twenty or more coordinate shells. Its intensity depends on the difference in scattering factors of the two species of atoms in the pair, a difference which can be enhanced by tuning the x-ray wavelength so that there is anomalous scattering from one type of atom. This tunability and the brightness of a synchrotron light source provide a figure of merit roughly 10^4 times greater than a 60 kW x-ray tube for such experiments. Diffuse scattering, then, is sensitive to density fluctuations associated with voids, clustering, and gross

molecular arrangements; it is sensitive also to any deviation from average atom-atom distance, thus to strain centers and to the presence of precipitates of interstitial atoms. To take an instance from technology, it is a method to study the organization of defects in ionic conductors, which make up important components of certain fuel cells now being developed.

X-ray diffraction topography permits the visualization of many types of crystal defects. It is used for routine quality control of crystal materials as well as for basic study of defect-conditioned properties of solids. In such applications synchrotron radiation has several advantages over conventional x-ray sources. A small degree of tilt of one crystal region with respect to another is spectrally compensated by the broad band of radiation and thus only regions of important strain are imaged. Resolution depends on source size; hence the small size of a synchrotron source can be translated into very high resolution and rapid data collection rate; in work done in Europe¹⁰ a thousandfold increase in rate has been obtained, exposure times are reduced from hours to seconds. There is a prospect of bringing this time down to the millisecond region for dynamic studies of crystal growth and plastic deformation.

3.3.3 Other x-ray applications:

Although some resonant Raman and some Compton scattering work has been done with synchrotron radiation, there has been little in the way of inelastic x-ray scattering experiments generally because the flux presently available is too low. The facility proposed here should make high resolution Raman, Compton and non-linear experiments quite feasible. In analogy with experience in non-linear optics at visible wavelengths, the prospects of exploring and perhaps exploiting non-linear phenomena at x-ray wavelengths seem quite exciting.

Potentially very important are microscopy and lithography carried out with soft x-rays at wavelengths of 10 to 20 Å, somewhat longer than we have generally been considering above. At these wavelengths synchrotron sources have no competition. In one class of microscopy, one places the specimen over a photoresistive wafer and illuminates the sample and wafer in the manner illustrated in Fig. 3-4. The photoresist is then developed and viewed with a scanning electron microscope. Radiation in the 10-20 Å region is desirable because it

FIGURE 3-4

(a) Irradiation of the x-ray resist through the specimen. In x-ray lithography the specimen is a mask generated by an electron beam. (b) The replica after development of the resist. The replica can be metallized and examined in a scanning electron microscope. In x-ray lithography the resist is completely removed in the fully exposed area, opening up this area for subsequent device fabrication steps (ref. 11).

provides greatest contrast, and the high collimation of the synchrotron source reduces blurring. Resolution of the order of $100 \text{ \AA}$ and exposure times of the order of 1 second appear practicable. Such resolution is lower than that attainable with electron microscopy, but this form of x-ray microscopy is much more sensitive to structural detail in the specimen interior and it is not restricted to a vacuum environment - wet samples may be studied. Electron and x-ray microscopy are thus complementary.

Essentially the same scheme is employed for lithography. In this application the specimen of Fig. 3-4 becomes the mask to be replicated. This appears to be a rapid, accurate and economical way for mass reproduction of sub-micron structures. An exploratory example obtained by Spiller and coworkers¹² appears in Fig. 3-5. The electrical industry has moved steadily towards smaller, higher density integrated circuitry and it is about to enter the submicron regime and soft x-ray lithography may prove to be the way to go. There will undoubtedly be other technological applications of this lithographic scheme: Fresnel zone plates for x-ray and UV wavelengths and microwave devices are but two examples.

There are other classes of microscopy. Horowitz, for one, devised¹³ a scheme wherein the specimen is translated past a pin hole x-ray source and the resultant fluorescence is monitored by an energy responsive detector. This is then a chemically sensitive method with great depth of field but low spatial resolution. Submicron scale quantitative analysis appears feasible with it.

References

1. D. E. Sayers, E. A. Stern, and F. W. Lytle, Phys. Rev. Lett. 35, 584 (1975).
2. P. Eisenberger, R. G. Schulman, and G. S. Brown, Proc. Nat. Acad. Sci. USA 73, 491 (1976).
3. R. G. Shulman, P. Eisenberger, W. E. Blumberg, and N. A. Stombaugh, Proc. Nat. Acad. Sci. USA 72, 4003 (1975).
4. J. Jakevic J. A. Kirby, M. P. Klein, A. S. Robertson, G. S. Brown, and P. Eisenberger (to appear).
5. S. P. Cramer, T. K. Eccles, F. Kutzler, K. O. Hodgson, and L. E. Mortenson, J. Am. Chem. Soc. 98, 1287 (1976).
6. Preliminary results are reported in J. C. Phillips, A. Wlodawer, M. N. Yevitz, and K. O. Hodgson, Proc. Nat. Acad. Sci. USA 73, 128 (1976).

a

b

c

Figure 3-5. Soft x-ray replications employing synchrotron radiation: a and b are of one micron width structures characteristic of integrated circuitry, c is of a segment of a Fresnel zone plate.

7. B. Buras, J. Staun Olsen, and L. Gerward, Nucl. Instr. and Meth. 135, 193 (1976). Application to low angle scattering is given in J. Bordas, I. H. Munro, and A. M. Glazer, Nature 262, 541 (1976).
8. E.g., see G. W. Stroke and M. Halioua, Bull. Am. Phys. Soc. 21, 622 (1976).
9. R. S. Goody, K. C. Holmes, H. G. Mannherz, J. Barrington Leigh, and G. Rosenbaum, Biophys. J. 15, 687 (1975).
10. T. Tuomi, K. Naukkarinen, and P. Rabe, Phys. Stat. Sol. A25, 93 (1974); M. Hart, J. Appl. Cryst. 8, 436 (1975); J. Bordas, S. M. Glazer, and H. Hauser, Phil. Mag. 32, 471 (1975); and B. K. Tanner, M. Safa, and D. Midgley (submitted to J. Appl. Cryst.).
11. E. Spiller, R. Feder, J. Topalian, D. E. Eastman, W. Gudat, and D. Sayre, Science 191, 1172 (1976).
12. E. Spiller, D. E. Eastman, R. Feder, W. D. Grobman, W. Gudat, and J. Topalian, J. Appl. Phys. (submitted).
13. P. Horowitz and J. A. Howell, Science 178, 608 (1972).

3.4 Research Relationships with Energy Technologies

It is clear from the preceding information that many of the investigations which would be carried out at this facility are closely related to the technological problems of energy and environment with which ERDA is concerned. Some examples of such relationships are the following:

The chemical state and local environment of elements which find their way into pollutant materials are of great concern in connection with the control of pollution levels. With synchrotron light one can obtain this kind of information about such species as lead, sulfur, and cadmium, in gases, liquids and solids, and on solid surfaces. Monitoring of dilute metal impurities in atmospheric samples thus done should provide insight into mechanisms of dispersal and possible methods for control. Studies of the impurities at the surface of a material will advance understanding of effects of atmospheric and water pollutants on the properties of the material in question. On a somewhat different front, transitions induced in gas atoms and molecules by photon absorption are directly involved in the behavior and reactions of the atmospheric ozone layer, as well as in the reactions of normal atmospheric constituents with "natural" and man-introduced pollutants. In the spectral regions active in the upper atmosphere, where important reactions occur, there are very few data; measurements with synchrotron radiation are crucial to this vital field.

In biological systems, energy production and other metabolic processes often involve complex molecular structures which undergo oxidation-reduction cycling, atom or electron transfer, and sometimes the storage of photon energy via photochemical and subsequent thermal reactions. Synchrotron light offers particular opportunities for studying such processes. As an example, it seems eminently worthwhile to study the function of nitrogenase, the enzyme in plant bacteria that catalyzes the conversion of atmospheric nitrogen to ammonia. If this conversion could be modeled in some perhaps non-enzymatic way there would be a potential for saving, worldwide, large amounts of energy now expended in the production of synthetic ammonia for fertilizers. Preliminary EXAFS studies of the enzyme have already yielded important information about the valence behavior of its active molybdenum site and about the atoms surrounding this site. Other biological systems may well play an increasing role in our energy economy and they, too, will require further study.

Structural and bonding effects at surfaces of metallic and nonconducting solids, which are studied in detail with several techniques mentioned in the preceding section, are the substance of corrosion behavior and catalysis; electronic structural effects at surfaces are determinants also of the properties of the various types of junctions in widely used semiconductor devices. Investigation of ordering behavior and its changes in solids related to those useful as high temperature insulators bears on one of the practical problems of MHD power generation. Similar investigations of superionic conductors could lead to new materials for barriers needed in certain types of high energy-density batteries.

Synchrotron radiation is especially powerful for the study of disordered materials, for studies useful in the engineering of glasses, for solar energy conversion, for the characterization of superconducting thin films, and for understanding the behavior of dilute atomic species (such as dispersed catalysts or the impurities which affect mechanical or electrical properties of materials). It seems practicable to monitor the activity and degradation of catalyst particles during function in reaction vessels or fuel cells.

The kinds of information which can be obtained by use of synchrotron sources about the electronic and spatial structures of metals and alloys and about the perturbations and transformations produced in these structures by heat, photons, and neutrons relate directly to vital materials problems in energy producing and control equipment. These problems are associated with fission or fusion reactors, hydrogen storage alloys, magnetohydrodynamic generators, and semiconductors. As an example, there is open the hitherto marginal prospect of deriving significant information from low angle diffraction about radiation-induced voids in reactor vessel materials.

Synchrotron radiation offers the possibility for studying dynamic behavior associated with many of the above-mentioned properties. The facility proposed would in a major way extend capabilities for much of this work beyond what can be done with available synchrotron light sources.

4. FACILITY DESIGN

4.1 Introduction

The overall layout of the synchrotron radiation facility is shown in Fig. 1-2. Electrons are injected from a 50-MeV linear accelerator into a 700-MeV "booster" synchrotron. Surrounding the linac and booster is the 2.5-GeV ring; injection takes place in one of the long straight sections of this ring. The 700-MeV ring is located nearby.

4.2 General Design Considerations

Basic considerations leading to the choice of magnet lattice, radio frequency accelerating system and injection energy will be discussed in the paragraphs that follow.

As mentioned in Section 2, the wavelength of the peak of the radiation spectrum is proportional to $1/(E^2 B)$ where E represents particle energy and B is the magnetic flux density at the orbit. The rf power, for a given circulating current is proportional to $E^3 B$. Thus, the wavelength of the spectrum peak can be shortened at less expense in rf power by increasing B than by raising E . Also, only a small portion of the radiation from the electrons distributed around the necessary 2π of bend can be brought out for use. These considerations lead to the concept of short sectors of high magnetic field interspersed among sectors of relatively low field.

The "lattice" of a synchrotron or storage ring is composed of a sequence of bending and focusing magnets. The functions of bending and focusing can be included in the same magnet or separate magnets can be used for bending and focusing. The latter "separated function" system is the one that is proposed for the rings in the synchrotron radiation facility. The bending magnets will be simple, C-shaped, parallel-pole electromagnets. Focusing will be accomplished by quadrupole magnets arranged either singly or in triplets. Higher order effects will be taken care of by inclusion of sextupole magnets and auxiliary windings on the pole faces of the bending magnets.

4.2.1 Electron dynamics

The radial and vertical motion through such a lattice is described in the classic paper of Courant and Snyder (Annals of Physics 3, 1 (1958)). An important function discussed by Courant and Snyder is the amplitude

function β . If x is the radial displacement from the "equilibrium orbit", y is the vertical displacement and s represents distance along the orbit then

$$x(s) = A_x \beta_x^{1/2}(s) \sin\left(\int \frac{ds}{\beta_x} + \varphi_x\right)$$

$$y(s) = A_y \beta_y^{1/2}(s) \sin\left(\int \frac{ds}{\beta_y} + \varphi_y\right)$$

where A_x , A_y , φ_x and φ_y are determined by initial conditions.

The amplitude function β has the periodicity of the magnet lattice; its value can be determined by methods described by Courant and Snyder. Numerous computer programs are available for its numerical determination.

When the distribution of the amplitudes and angles of the paths of all of the electrons in a beam are plotted in x - x' or y - y' phase space the area of the distribution (usually roughly elliptical in shape) is referred to as the "emittance" of the beam.

As can easily be seen from the expressions for $x(s)$ and $y(s)$ the beam size will vary as $\beta_x^{1/2}$ and $\beta_y^{1/2}$ around the machine. Low β points are provided at a number of places in both the UV and X-ray rings to give maximum beam brightness.

One wavelength of the "betatron oscillation" is completed when

$$\int_{s_1}^{s_2} \frac{ds}{\beta} = 2\pi$$

Integration around the complete circumference will now yield the ν -value, the total number of betatron oscillation periods in one revolution. To avoid destructive resonance effects the machine should be designed to have a ν -value that is not close to an integer plus a small rational fraction.

An off-momentum particle will travel on a different equilibrium orbit which, in general, is not parallel to the central orbit but will have wiggles correlated with the magnet lattice. The momentum dispersion function $X_p(s)$ is defined as

$$\Delta x(s) = X_p(s) \frac{\Delta p}{p_0}$$

where $\Delta x(s)$ is the local setover of the equilibrium orbit for a momentum deviation Δp from the central orbit corresponding to the momentum p_0 . Like the β -function, $X_p(s)$ has the periodicity of the magnet lattice.

As can easily be seen from Sect. 2.2 the voltage per turn in kV necessary to make up for the radiation loss is given by

$$V_r = 88.5 E^4 / \rho \quad (E \text{ in GeV, } \rho \text{ in m})$$

During the acceleration cycle an additional voltage V_a (keV/turn) is required.

Here

$$V_a = C \dot{B}_0 \times 10^{-4} \text{ keV}$$

where C is the ring circumference in m,

$\dot{B}_0$ the magnetic guide field rise rate in kilogauss/sec.

The rf system that will supply the voltage has to operate at a frequency which is an integer (h , the harmonic number) times the revolution frequency of the electrons. Under these conditions, particles with momentum and phase (relative to the rf voltage) within a range around the stable phase angle (see below) and the central momentum, will undergo stable phase or synchrotron oscillations. The stable regions in longitudinal phase space are called rf "buckets". There will be h equally spaced such buckets and the electron beam can occupy any number of buckets, depending on the filling mode. In other words, the electron beam will be in the form of 1 to h bunches. In order for the electron bunches to fit inside the rf buckets it is necessary that the applied gap voltage V be greater than V_r in the storage mode and greater than $V_r + V_a$ in accelerating mode. The stable angle ψ_0 is given by

$$\sin \psi_0 = \frac{V_r}{V} \text{ or } \sin \psi_0 = \frac{V_r + V_a}{V}$$

4.2.2 Radiation and damping:

The emitted radiation affects the longitudinal as well as the transverse motion.

An electron whose energy deviates from the normal energy will, during one revolution, emit a slightly different amount of energy. The reason is not only the different particle energy, but also the fact that an off-momentum particle travels on a somewhat different path in the bending magnets where the radiation is emitted. This in turn leads to damping of the energy (or phase) oscillation amplitudes.

The radiation effects on the transverse oscillations are different in the vertical and horizontal planes. During the rf acceleration that takes place every revolution to make up for the radiation loss, there is a reduction in the otherwise invariant vertical oscillation constant A_y , introduced earlier, equivalent to damping of the vertical oscillation amplitude. The same is true for the motion in the radial plane, but here an additional effect causes antidamping rather than damping. When the electron emits radiation in the bending magnets it moves to a different equilibrium orbit and there will be a change in the horizontal oscillation amplitude which is measured with respect to the instantaneous equilibrium orbit. This, together with the fact that the amount of radiated energy itself depends on the radial betatron amplitude accounts for the antidamping. Fortunately, in a separated function machine with parallel edge bending magnets the antidamping effect is zero and the entire radial damping effect obtained from the interaction of the electrons with the longitudinal rf accelerating field remains.

The effect of radiation on the synchrotron and radial betatron oscillations would be pure damping, resulting in negligibly small beam sizes, if the energy loss were a continuous process. Because the radiation is emitted in discrete quanta the damping effects in the longitudinal and radial phase planes are counteracted by excitation of random walk type oscillations resulting in finite longitudinal and horizontal beam sizes. Radiation excitation of vertical oscillations comes from the finite but very small forward angle with which the radiation is emitted and can in general be neglected. Finite vertical emittance is the result of linear coupling to the horizontal motion; this coupling always exists in the ring because of magnet imperfections.

The radial emittance is highly affected by the size of the momentum dispersion function in the bending magnets, with low X_p values leading to small emittances.

In the present X-ray ring designs this fact has been utilized in a double sense:

1. The regular bending magnets are incorporated in achromatic arcs in which the X_p function stays below 0.5 m. Disregarding the wigglers, such a design results in a radial emittance about an order of magnitude smaller than that found in more conventional electron rings of comparable energy.

2. The high field magnets (wigglers) are placed in the center of insertions in which the X_p function is matched to zero outside the wigglers and reaches a maximum as low as 0.005 m inside the wigglers. This prevents any significant increase in the radial emittance when the wigglers are turned on. (In fact, in the present design, there is a slight decrease in the radial emittance coming from increased radial damping when the wigglers are on.)

Similar design criteria have been used for the UV ring.

4.2.3 Space charge and instabilities:

With a current of a significant fraction of an ampere, intensity related effects are to be expected.

The space charge defocussing effect coming from the electromagnetic field, produced directly or indirectly by the beam is negligible for highly relativistic particles such as 1 - 2 GeV electrons.

A space charge effect that will reduce the lifetime of the beam is the so-called Touschek effect wherein transverse momentum is transferred into longitudinal momentum by Coulomb scattering between particles. The bunches will grow in longitudinal phase space and eventually spill outside the rf buckets. The Touschek lifetime is inversely proportional to the charge density of each bunch and consequently will be particularly short in the present design where the transverse beam dimensions are purposely minimized to achieve large beam brightness.

Transverse and longitudinal instabilities will be excited whenever there is a proper phase difference between the coherent oscillations of the beam bunches and the electromagnetic forces induced by such oscillations in the environment of the beam such as the vacuum chamber and the rf cavities.

In electron rings a single bunch transverse instability of the head-tail type is usually the most bothersome. Particles at the head of the tight bunches exert transverse forces on the particles at their tails through the wake fields due to finite resistivity of the vacuum chamber. However, as long as the chromaticity, defined as $p \frac{dv}{dp}$ is positive and greater than a given value, all important oscillation modes will be stable. Hence it is necessary to install sufficiently strong sextupoles not only to cancel the existing natural negative chromaticity originating in the momentum dependent quadrupole focussing strength, but also to produce the necessary positive value of this parameter.

Other instabilities to be expected are caused by higher mode excitation in the rf cavities and various parts of the vacuum chamber; these lead to heat losses as well. They can be suppressed by installing damping loops in the rf cavities and by placing resistive absorbers in proper positions in the vacuum pipe, which itself will be designed to minimize rf excitation. Multibunch modes, in which the bunches "talk to each other" can also be eliminated by decoupling the bunch motion transversely by use of an rf quadrupole and longitudinally by installing a second rf system operating on a different harmonic number. Feedback can also be used to damp various instabilities. A low harmonic number is desirable to minimize most of these effects and a radio-frequency of ~ 50 MHz ($h = 24$) was chosen as a compromise to avoid excessively large rf cavities.

The high intensity effects described above have dictated the injection energy of 700 MeV in both storage rings. Extrapolation of experience gained at CEA and DORIS with operation in a many bunch mode indicates that accumulation of a beam current of ~ 1 A is feasible at this energy.

4.3 X-ray Ring

4.3.1 Lattice and magnets:

The lattice of the X-ray ring consists of six arcs matched to six insertions. The layout of one of the six identical sectors is shown in Fig. 4-1 and its β and X_p functions are plotted in Fig. 4-2. Each arc is made up of two achromatic bends separated by a quadrupole triplet. As mentioned earlier, the horizontal dispersion function ($X_p(s)$) stays below 0.5 m in this design and the radial emittance is about an order of magnitude smaller than that found in more conventional electron rings of comparable energy, designed for colliding beam experiments. The beam is brought to a low - β focus ($\beta_x = 0.57$ m, $\beta_y = 0.35$ m), in the center of each insertion by triplets adjacent to the arcs. The insertion center is also the location of the high-magnetic-field "wiggler". It comprises three superconducting dipoles operating at fields corresponding to bends of 3.0° - 6.0° and 3.0° at 2.5 GeV. The fields will be of the order of 40 kilogauss. Such a dipole triplet restores the beam to the equilibrium orbit and has only a small effect on the radial emittance. It can be operated at fields bearing any desired ratio to the fields in the arcs, or turned off. Although it is tempting to consider single high-field magnets, the fields in such single dipoles must be tracked with the fields in

FIGURE 4-1
Sextant of 2.5 GeV Ring

FIGURE 4-2
Amplitude and Momentum
Dispersion Functions, β and X_p

the other dipoles; the disadvantages outweigh the saving in rf power. (Less than half of the radiation from the wiggler triplet can be brought out of the ring and therefore much of the power is "wasted"). Two sets of sextupoles (12 and 24 respectively) are required to compensate for the relatively large horizontal and vertical chromaticity. Sextupoles will be combined with quadrupoles in the center of each achromatic bend while sextupoles will be placed between the two dipoles in each half of these bends.

The bending magnets will be C-shaped and conventional in design. A cross section of a typical bending magnet is shown in Fig. 4-3. The same magnet cross section will be used both in the X-ray ring and in the UV ring; thus magnet laminations produced by the same die can be used in the magnets of both rings. A quadrupole is shown in section in Fig. 4-4.

The lattice described requires some of the radiation beams to penetrate the outer edge of the quadrupole structures; apparently a slot is required making the quadrupole structure analogous to a C-shaped dipole. Such magnets are feasible, judging from experience with narrow quadrupoles for beam transport which have been built at Brookhaven for several years. Although the side sections of the iron yokes of these quadrupoles are omitted, they still provide good field patterns. The side coil can be split and the two magnet halves separated to create a slotted quadrupole; the field shape can be corrected by contouring the iron and by adding correction coils. Quadrupole pole tip fields no higher than 10 kilogauss will be required. The sextupoles will be slotted to make it possible to bring out a light beam from the adjacent bending magnets.

Altogether 36 ports will be available in the arcs. Most of these can be provided with dual beam pipes to supply a total of sixty experimental setups. At 2.5 GeV the radiation spectra from these ports will peak at $3 \text{ \AA}$.

Radiation from each wiggler magnet which will be operated at a field of about 40 kilogauss will have $\lambda_c = 0.7 \text{ \AA}$ for an electron energy of 2.5 GeV. Each wiggler will provide radiation for 3 beams so with six wigglers in operation 18 beams would be provided with radiation in the hard X-ray region.

FIGURE 4-3
BENDING MAGNET

FIGURE 4-4
QUADRUPOLE MAGNET

Future use of helical wigglers is not excluded in the present design. Such wigglers would require free straight sections of the order of 5 m in length. A small dipole and an additional quadrupole would be required at each end of these straight sections to preserve the equilibrium orbit of the machine and to accomplish matching of the helical wigglers to the ring. Alternate use of the longer straight sections for helical and ordinary wigglers is possible. However, if the low β -values of the shorter straight sections are to be reproduced, additional double focussing doublets or triplets will have to be introduced into the longer insertions.

The leading parameters of the 2.5-GeV ring are summarized in Table 4.1.

TABLE 4.1
X-ray Ring

The ring of six superperiods would have the following parameters:

Length of one arc		15.2 m
Length of insertion		8.2 m
Circumference		140.5 m
$R = C/2\pi$		22.4 m
ρ (in BB)		8.17m
R/ρ		2.74m
$B\rho$	50.1 (1.5 GeV)	83.5 kG-m (2.5 GeV)
B	6.13(1.5 GeV)	10.22kG (2.5 GeV)
Number of bending magnets		48
Weight of each		3000 lb
Power at 2.5 GeV		550 kW
Number of quadrupoles		66
Number of sextupoles		36
Number of wigglers		6
Max. Wiggler length	0.08 0.16	0.08 cm
Max. Wiggler Field		40 kG

Dynamic characteristics of the beam would be approximately:

ν_x	11.4
ν_y	6.8
$dv/(dp/p)$ uncorrected x	-30
uncorrected y	-27

v_s	0.001
τ_x damping time at 1.5 GeV	9.5 msec
τ_y	9.5 msec
τ_s	4.7 msec
f_o rotation frequency	2.2 MHz
f radio frequency (depending on user requirements this may be doubled)	53.5 MHz
h harmonic number	24 (48)
Power to beam	

	<u>Ring</u>	<u>Transverse Wigglers</u>	<u>Total</u>
1.5 GeV	55 kw/A	88 kw/A	143 kw/A
2.0 GeV	173	155	328
2.5 GeV	427	245	672
No. of cavities			2
Peak voltage, each cavity			400 kV
Touschek life (small bunch lengthening) 1A, 1.5 GeV			1 hr.

4.3.2 Radiofrequency system:

The energy loss per turn of a 2.5 GeV electron as it passes through the 10 kG bending magnets is 427 keV. In the six 40 kG wigglers, the energy loss will be 245 keV. With a beam current of 0.5 ampere, the total rf power, including cavity losses, will approach 600 kW. Peak voltages on each of two cavities will be about 400 kV.

To minimize operating costs the power amplifiers which drive the rf accelerating cavities must operate at high efficiency and must have long lives. High power tubes are available with reasonable characteristics, yielding power of the order of 500 kW cw, up to about 100 MHz. At this frequency, tube efficiency is beginning to deteriorate and it seems wise to choose an operating frequency of about 50 MHz, corresponding to a harmonic number of the order of 24.

4.3.3 Vacuum system:

An ultrahigh vacuum will be required; it will be necessary to achieve pressures of 10^{-10} Torr without beam and 10^{-9} Torr with full beam.

Experience with storage rings elsewhere indicates that satisfactory performance can be expected from an extruded aluminum chamber with an integral water cooling channel and with distributed titanium pumping to collect the large quantities of gas liberated when the wall is bombarded by radiation. Vacuum chamber cross sections suitable for inclusion in bending and quadrupole magnets are shown in Figs. 4-5 and 4-6.

The entire chamber will be surrounded by heaters for bakeout to temperatures of 150-200°C. Experience at the CERN ISR has shown that this process is needed rather infrequently but is essential occasionally.

Special care in design of the cooling system is required where side pipes are included for transmission of radiation to experimental apparatus. Also, where superconducting components are used as in the high field wigglers, low temperature components must be protected from radiation. In general the angular deflections in high field wigglers will be small enough that the radiation will travel an appreciable distance before impinging on the wall. Special attention will be given to portions of the chamber on the inner circumference just downstream from the wigglers.

4.4 UV Ring

A small 700 MeV ring intended for users interested in the UV region of synchrotron radiation, has also been designed. Its general layout is shown in plan in Fig. 4-7 and in perspective in Fig. 4-8. As in the 2 GeV ring its lattice configuration is aimed at minimizing the electron beam emittance. The ring consists of four achromatic arcs connected by straight sections. The straight sections, which are designed as matched insertions, will be used for wigglers of either the conventional or the helical type. They will also be used for injection and rf acceleration. The maximum field in the bending magnets is ~12 kG. The horizontally focusing quadrupoles QF between the two dipoles in each arc make the horizontal dispersion function zero outside the area. This function reaches a maximum of ~1 m in quadrupoles QF. The triplets adjacent to the arc focus the beam at the center of the straight section. Depending on the settings of the triplets two sets of β -values (low and high) can be obtained at the insertion centers. For conventional wigglers low β values are desirable to achieve high beam brightness, while the high β values are necessary to optically match the helical wiggler to the ring. High β values are also required for injection to avoid an excessively thin septum in

FIGURE 4-5
VACUUM CHAMBER
BENDING MAGNET

FIGURE 4-6
VACUUM CHAMBER
QUADRUPOLE MAGNET

FIGURE 4-7
700 MeV RING

FIGURE 4-8
SKETCH OF 700 MeV RING

the injection magnet. Sextupoles SF and SD will control the chromaticity of the ring. β and X_p functions are shown in Fig. 4-9. A summary of the basic machine parameters are given in Table 4-2.

The energy loss per turn in the ring (not including wigglers) is 11 keV at 700 MeV. It will be supplied by ~ 50 MHz rf cavity with a gap voltage of 100 KV. Although an adequate quantum lifetime can be achieved with much lower voltage levels, a gap voltage of 100 kV will give a sufficiently large rf bucket to ensure an acceptable Touschek lifetime. With a circulating beam current of 1 A, taking into account bunch lengthening, a beam life of ~ 2 hours can be expected. The total rf power, including cavity losses, will be ~ 20 KW.

TABLE 4.2

UV Ring

Energy	700	MeV
Circumference	44	m
Revolution Time	0.15	sec
Bending Radius	1.9	m
ν_x^*	~ 4.1	
ν_y^*	~ 2.8	
Momentum Compaction Factor	0.02	
Horizontal Damping Time	0.02	sec
Vertical Damping Time	0.02	sec
Longitudinal Damping Time	0.01	sec
Horizontal rms Emittance	$3.8 \pi \times 10^{-8}$	mm ²
Harmonic Number	7	

* Assumes two low β and two high β insertions.

4.5 Injection

The injection system will consist of a 50 MeV linac and 700 MeV booster synchrotron. This combination is required to achieve circulating currents of 1 A in both the UV and the X-ray rings. The radial betatron motion in the booster has to be damped if helical wigglers are to be used in conjunction with the storage rings. This is because the vacuum chamber aperture will be constricted to about 1 cm at the location of the wigglers.

A simple separated function booster has been designed consisting of two 180° arcs, each containing 3 FODO cells. The lattice is shown in Fig. 4-10.

FIGURE 4-9
 β and X_p functions, 700 MeV ring.

FIGURE 4-10
Booster Lattice

Straight sections, 1.5 m in length, connect the two arcs. These are inserted between the two halves of a cell defocusing quadrupole. In this way, the X_p function stays matched while the periodic variation of the β -function in the cell will be somewhat perturbed. The maximum values of β_x and β_y are 11.4 and 7.5 m.

The magnetic field in the dipoles is 8.15 kg at 700 MeV. One of the straight sections will be used for injection and for rf acceleration, the other for ejection.

A ~ 50 MHz rf system results in a harmonic number of 6. Injection and ejection kicker demands can be greatly reduced by chopping the linac beam and filling only one or two out of the six rf buckets. With a 20 mA linac current and a 0.75 sec acceleration cycle (0.25 sec flat top) it will not take more than 9 and 3 minutes to fill the 2 GeV and 700 MeV ring, respectively.

The energy loss per turn in the synchrotron booster is 7.5 keV at 700 MeV

Shielding

4.6.1 Basic requirements:

Experiments using synchrotron radiation will, on occasion, require optical elements close to the electron beam, perhaps even in the main vacuum of the machine. Moreover, to avoid the complication and expense of remote control, it is important that the experimenters have access to this close-in apparatus.

At the same time it must be recognized that because conditions can arise under which intolerably high radiation levels exist around the machine, shielding is required. Photoneutrons and bremsstrahlung are of principal concern in the design of this shielding, which must protect experimenters and apparatus.

In this section we present a possible shielding configuration. An attempt has been made to provide acceptable protection against radiation under all conditions, while preserving accessibility as far as possible. This design study is still in progress; it is our hope that the amount of shielding proposed here can be reduced or rearranged to make experimental operation still more convenient.

4.6.2 Studies and experience elsewhere:

A considerable amount of experience and understanding of the shielding of electron synchrotrons and storage rings operating in the energy range up to and well above 2.5 GeV has been accumulated in a number of laboratories. Results and data that we have found helpful include the work of Alsmiller and his associates,^{1,2,3} the AEC New York Operations Office Shielding Tables,⁴ the CEA work described in CEAL-TM-198,⁵ and the SPEAR shielding report,⁶ together with later experimental data from SPEAR for which we are indebted to John L. Harris and his associates at SLAC.

Gabriel and Alsmiller¹ have estimated photoneutron production by electrons of energies up to 400 MeV assuming that the electrons impinge on a thick target. They have shown that the relation between neutron yield and the ratio $\frac{\text{neutron energy}}{\text{incident electron energy}}$ is essentially independent of incident electron energy over the electron energy range between 100 and 400 MeV. This result is shown in Fig. 4-10, in which the yield for neutrons produced at angles between 60° and 120° to the initial electron direction is plotted against the ratio mentioned above. The yield is as much as 50% higher for neutrons produced at angles between 0 and 30° off axis and drops to lower values for backward directions. Application of the curve shown in Fig. 4-11 to photoneutron production at 2 GeV implies a rather long extrapolation, but the results prove to be in reasonably good agreement with experience in the 2-GeV range.

The conclusion from these considerations and others to be mentioned later is that a reasonable shielding system for the 2.5-GeV ring is comprised of a judicious installation of lead collimators and shields very close to the main vacuum chamber and a concrete enclosure with walls about 2 feet thick and a roof somewhat thinner, if it is needed at all.

The CEA authors proposed a circumferential 4-inch thick lead shield, which they felt would be adequate, without additional concrete, to

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1. T. A. Gabriel and R. G. Alsmiller, Jr., Oak Ridge Report, ORNL-4443, 1969.
 2. R. G. Alsmiller, Jr. and J. Barish, Particle Accelerators 5, 155 (1973).
 3. R. W. Roussin, R. G. Alsmiller and J. Barish, Nuc. Eng. Design 24, 250 (1973).
 4. "Tables for the Determination of the Lateral Shielding Requirement of High Energy Accelerators" New York Operations Office, AEC, HASL-303, 1968.
 5. B. J. Maddox and H. Winick, CEA Report, CEAL-TM-198, 1973.
 6. J. L. Harris and T. Jenkins, SLAC Report, SPEAR-106, 1971.

FIGURE 4-11

Photoneutron production (Gabriel and Alsmiller).

shield a 100 mA 3.5 GeV electric beam "even in the event of a worst-case beam dump". They performed preliminary experiments with the CEA machine, but the demise of that machine precluded a convincing demonstration of the adequacy of their scheme.

At SPEAR it was concluded that, with lead collimators located at 5-10 ft. intervals and with a 2-foot thick concrete wall, a catastrophic dump at one point of 10^{13} 3-GeV electrons could result in a peak radiation level outside of the shield of 530 mR. If this loss were distributed around the ring the average radiation level would be 5.5 mR. The beam life at SPEAR is 1-2 hours; at the end of that time the beam current has fallen to a fraction of the order of one-half of its original value. At this time the remainder of the beam is deposited in a well-shielded dump. Consequently, for each charging of the ring an average radiation dose of 2-3 mR should be accumulated.

During operation at SPEAR radiation levels have been monitored at some 35 locations outside the concrete shielding tunnel. Typical readings during the first quarter of 1976 indicate accumulations of from 14 to 90 mrad of photons and from 4 to 77 mrem of neutrons. Average values are 38 mrad of photons and 34 mrem of neutrons. During this period 2.2×10^{-4} coulombs of 2.25- to 3.4-GeV electrons were injected into the machine (total charge is known to within a factor of 5). This would correspond to 130×10^{13} electrons. Hence the observed radiation doses are lower by more than an order of magnitude than those predicted.

4.6.3 Shielding for the 2.5-GeV ring:

From Gabriel and Alsmiller's curve (Fig. 4-11) it is possible to estimate dosage to a bystander from a localized beam dump. For a 1-ampere, (2.8×10^{12} electrons circulating) 2.5-GeV beam the dosage of photon-neutrons to a bystander 2 feet from a full beam dump is presented in Table 4-3 in several neutron energy bins. It is assumed for this calculation that the thickness of the material in which the beam dump occurs is adequate for photon-neutron production but provides no shielding. The effect of an 85-cm shielding wall is also included in Table 4-3, calculated from the results of Roussin et al.³.

TABLE 4.3

Photoneutron dosage associated with a full beam dump on the 2.5-GeV ring

Neutron Energy	Unshielded Dosage at 2 ft. (62 cm)	Dosage after inclusion of 85 cm of light concrete shielding*
(MeV)	(mR)	(mR)
0-100	142	15
100-200	40	10
200-300	18	5
300-400	9	5
above 400	<u>17</u>	<u>9</u>
TOTAL	226	TOTAL 44

* The dosage is thus measured at 85 cm from the point of beam dump.

Roussin's results, scaled to 2.5 GeV, are tabulated for passage of the various neutron groups through 200 gm/cm^2 (about 85 cm of concrete) shielding. The shield is assumed to be in contact with the vacuum chamber wall and the dose is measured at a point just outside, (i.e. 85 cm from the point of beam dump). Part of the reduction is associated with increased distance. Inclusion of tunnel space between the ring and its shielding further increases distance, reducing dosage by another factor of 4 or 5.

If the SPEAR estimates are converted to a circulating current of 2.8×10^{12} electrons at 2.5 GeV, we find that a catastrophic localized dump should give about 1 mR. This prediction is within about a factor of two of the calculation based on extrapolation of Alsmiller's work; in this area the two results must be considered to be in reasonable agreement. Evidently, from the SPEAR measurements, both results are pessimistic.

From these studies it seems reasonable to include, initially, two feet of concrete outside of the ring. This shield would be made of large concrete blocks except for the section near the plane of the electron beam, which should be built of small blocks for ease of rearrangement around beam ports.

The amount of concrete needed inside the ring and in a roof is not yet clear. Our conservative design includes a 2-foot wall inside the ring and a 1-foot thick roof, but, in view of the extra shielding offered by the magnet structures, these dimensions are certainly excessive.

Detailed design of beam ports should indicate how much lead shielding can be included next to the beam. As was suggested at CEA, lead will reduce materially the thickness required of the concrete, at least in specific locations.

4.6.4 Shielding for the 700 MeV ring:

Radiation levels due to local spills on the 700-MeV ring will be lower by an order of magnitude than those for the 2.5-GeV ring. This is due to the fact that the total charge stored is lower by a factor of three and to the lower electron energy. Hence the unshielded dosage at a distance of 2 feet from the beam dump will be of the order of 20 mR, which is less than the dose expected even behind the shield of the 2.5-GeV ring. Evidently, no concrete shielding tunnel is required for the 700-MeV ring. Adequate protection will be provided by a fence that prevents too close approach to the electron orbit and by lead shielding mounted in the magnet gaps.

4.6.5 Shielding for the linac and booster synchrotron:

Personnel outside of the 2.5-GeV ring will be reasonably well shielded from the acceleration and transfer processes in the 50-MeV linac injector and the booster synchrotron. If access to the inside of the 2.5-GeV ring is contemplated during operation of the injector system, it will be necessary to include some shielding, of the order of 2 feet of concrete, downstream of the linac and around the point of injection into the booster. Local shielding may be needed elsewhere in the booster. The amount of charge in the booster at any moment will not be greater than about 5×10^9 electrons, less by a factor of about 500 than the amount of charge to be stored in the 2.5-GeV ring.

4.6.6 Radiation during the injection process:

The injection process involves successive transfers of booster-accelerated charges, of the order of 5×10^9 electrons, into one or the other of the storage rings. The booster cycle takes about one second; hence to build up a charge of 3×10^{12} electrons in the 2.5-GeV ring or 10^{12} electrons in the 700-MeV ring will require about 10 minutes and 3 minutes respectively.

In principle, the injection process can be managed with such efficiency that virtually no loss takes place. In practice it is much easier to tolerate losses and take longer for injection. In this case extra local shielding may be required. An alternative is to accept the practice of some

synchrotron radiation facilities and to clear the floor of personnel during injection. Efforts will be made to avoid this, but it may be inevitable during the machine's early operating period.

4.6.7 Shielding of experimental beam lines:

The numerous beam ports through which ultraviolet and X-ray beams emerge to the experimental equipment introduce potential radiation hazards. Electrons cannot be permitted to stray from the beam and strike the wall at points visible through a beam port. To prevent this, collimators will be introduced at appropriate points upstream from beam ports.

Charged particles entering experimental beams will be swept to one side by permanent magnets.

All areas occupied by experimentalists will have radiation levels carefully monitored at all times and appropriate measures will be taken to keep radiation doses at safe levels. The technology to achieve safety already resides in Brookhaven's Health Physics groups associated with the high energy physics and other programs.

5. WIGGLERS

5.1 Introduction

For electrons of a given energy, radiation of the shortest wavelength will be obtained from the sections of the orbit with the smallest radius of curvature, hence with the highest magnetic field. It seems unwise to apply high fields in all of the bending magnets since only a fraction of the radiation emitted can be utilized while the unutilized radiation still is powered from the radiofrequency accelerating system. A more efficient approach is to include short regions of high field in the lattice insertions. To make the high field regions variable independently of the rest of the ring, they are designed in such a fashion as to restore the electron beam to the equilibrium orbit for all values of the high field. One method of achieving this is to alternate high fields of opposite polarity in such a way that the net deflection of the electron beam is zero (see Fig. 5-1). This arrangement is known as a "transverse wiggler" or, sometimes, as a "conventional wiggler". As mentioned above, wigglers of this type can be used to produce spectra at the shortest wavelengths.

Another type of wiggler involves a system in which a transverse field is applied in a direction which rotates along the electron orbit. This "helical wiggler" yields a spectrum peaked at somewhat longer wavelengths but which has the advantage of being much narrower than that of ordinary synchrotron radiation.

5.2 Transverse Wigglers

Fields of 40-60 kilogauss can readily be generated in superconducting windings. Figure 5-2 shows one possible configuration and the field pattern which it will provide. Coils are located above and below the orbit separated by a sufficient distance to allow passage of the beam and transmission of the emitted radiation. In the figure a beam energy of 1.5 GeV is assumed. The beam deflections are 5° in the initial and final fields and -10° in the central field.

The critical wavelength λ_c of the spectrum from a 2.5-GeV electron in a field of 40 kilogauss is about $0.7 \text{ \AA}$. If the field is increased to 60 kilogauss the critical wavelength will be reduced to about $0.5 \text{ \AA}$.

WIGGLER

FIGURE 5-1
Conventional wiggler.

FIGURE 5-2
Calculated wiggler field pattern.

At a focal point of a low emittance storage ring, this wiggler would give the smallest and brightest x-ray source available with present technology.

Wigglers can be used also to produce spectra at longer wavelengths in high energy rings. In the 2.5-GeV ring, for example, where the radiation from the orbits in the arc bending magnets has a λ_c of about 3 Å, spectra peaking at much longer wavelengths can be obtained by running the wigglers at low fields. If, for example, a spectrum with $\lambda_c = 40$ Å is desired, it can be obtained by running the wiggler with fields of less than one kilogauss.

The superconducting wiggler coils will each require about 3 million ampere-turns. In the coils themselves there will be no losses so the only demands on the cooling system will follow from lead losses and from direct thermal conduction through the wall of the dewar system in which the coils are enclosed. It is estimated that about 20 liters of helium per hour will be evaporated. The losses can be reduced by short circuiting the coils and operating them in the persistent superconducting mode.

A conceptual superconducting wiggler design has been presented in the report "Superconducting Wiggler Magnet for the Proposed BNL Electron Storage Ring" by Dahl and Sampson (BNL 20079). Further work by Dahl indicates that higher and better field patterns can be achieved by enclosing the superconducting coils in iron.

5.3 Helical Wigglers

Recent studies by B. Kincaid (to be published in the Journal of Applied Physics) indicate that the inclusion of "helical wigglers" in storage rings would yield circularly polarized light sources of high spectral purity leading to a flux (defined as number of photons per second per unit bandwidth and per unit solid angle) more than four orders of magnitude greater than that obtained from ordinary bending magnets.

The helical wiggler is a variant of the "free electron laser" evolved at Stanford and recently tested using a beam from one of the Stanford electron linacs. In this device a transverse magnetic field is generated whose direction rotates continuously with distance along the axis - the axis being coincident with the axis of the electron beam. Such a field can be generated by excitation of an open helical winding like that shown in Fig. 5-3. In the open

FIGURE 5-3
HELICAL WIGGLER

spaces between the turns of one winding, a second is wound and is excited with current flowing in the direction opposite to the current in the original winding. This current combination produces a field pattern with a zero axial component on the axis and with a transverse component which rotates with the same period as the pitch of either helix. The transverse field varies slowly near the axis, then increases rapidly as the winding is approached; this variation places severe limits on achievable transverse fields and on the useful thickness of the winding. For example, to obtain transverse fields of 6 kilogauss in a helix of pitch 2 cm, the maximum inner diameter of the wiggler will be about 1 cm and current densities of the order of $50,000 \text{ amperes/cm}^2$ will be required. Evidently only superconducting windings will be usable.

The electron orbits in the field patterns described above were traced in a number of computer runs and were found to agree with orbits derived from an approximate form of the equations of motion. The primary motion is helical with an orbit radius that is a small fraction of a millimeter and a pitch which is the same as that of the transverse field. The instantaneous axis of the helix is tangent to a sinusoidal "betatron oscillation" which lies in a plane through the axis of the wiggler. For a range of possible wiggler parameters the frequency of this oscillation is two to four orders of magnitude slower than that of the helical motion. Its phase and amplitude are determined by initial conditions. By a suitable (non-zero) choice of initial transverse velocities the amplitude of the betatron oscillation can be reduced to negligible values; with this correction all electrons, including those off axis will pursue helical paths whose axes are parallel to the wiggler axis and whose radii are almost identical. This work is described in a paper by J. P. Blewett and R. Chasman (to be published in the Journal of Applied Physics). This paper and Kincaid's are included in Vol. 2 of this Proposal.

The spectrum emitted by this wiggler will be peaked at a wavelength which is approximately the pitch of the helix divided by γ^2 where γ is the ratio of the electron energy to its rest energy. Thus, for a 2.5-GeV electron in a helix of 2-cm pitch, the spectrum will be peaked at about $10 \text{ \AA}$. The fractional bandwidth of the spectrum will be approximately $1/N$ where N is the number of turns in the helical winding.

The primary helical motion of the electron will have such a small diameter that its pitch angle will be of the same order as the angular width of the

radiation cone emitted by the electron. Thus the radiation pattern emitted through the end of the wiggler will be a cone whose outer edge makes an angle with the wiggler axis which is the sum of radiation cone angle and the pitch angle of the electron's helical motion.

The general behavior of electrons in the 20 MeV range in a helical wiggler has been checked at Stanford.

Recently, wigglers with sinusoidally varying vertical fields have also been considered by Kincaid. He concludes that the spectrum emitted by such wigglers is identical with that from the helical wiggler provided that the peak magnetic fields and pitches are the same. However, the total amount of radiated power is lower by a factor of two and the radiation will be linearly rather than circularly polarized.

6. EXPERIMENTAL FACILITIES

The monochromators, detectors, data acquisition systems, vacuum gear, and other items of highly specialized equipment required for research in the photon beams emerging from the storage rings are not ordinarily found in the individual armamentarium of a visiting user. Rather, such apparatus constitutes an essential part of the facility for use in common. This equipment is not inexpensive and a substantial allocation of funds must be made for it. A single, typically instrumented beam line costs several hundred thousand dollars. For a number of reasons, it is essential that development and assembly of this research equipment should proceed during the period of major construction. This is obviously the case for certain components which become in effect elements of the storage ring vacuum systems. Further, if experimenters are to gain maximum advantage of the exceptional qualities that the light sources at the rings will provide, design of certain important parts of this equipment, which are hardly off-the-shelf material, should proceed in parallel and in interaction with the design of certain components of the rings. Indeed, some of this equipment is needed for testing and tuning the rings. Finally, the period of major construction can be usefully employed for equipment development and for strengthening at the Laboratory those instrumentation areas most heavily involved in the research to be carried on at the facility.

There are funds specifically designated in the construction budget to provide a modest inventory of apparatus for the purposes outlined above: testing and tuning the storage rings and starting the experimental program. A continuing research and development effort will be required on some special items and in time a sizeable capital investment will go for equipping additional beam lines and for meeting the demands of an expanding and evolving research activity. These R&D and capital needs are noted in Section 8. A detailed discussion of instrumentation follows.

To a certain extent, equipment for research with synchrotron radiation can be classified according to the wavelength range in which it is designed to operate. It is wavelength which determines whether a crystal or one of a number of types of grating should be chosen for a monochromator; which fixes requirements for local shielding; and which dictates whether a line is to be coupled to the large or to the small ring, to a wiggler or to a bending magnet section. It even influences the vacuum design through the availability, for some wavelength

regions, of photon transmitting windows which isolate and thus protect the ring vacuum. Even in a given wavelength region, however, various experiments impose their specific demands, which are reflected in design of instruments. For example, a single type of x-ray monochromator does not provide optimum performance for crystal diffraction, for small angle scattering and for extended x-ray absorption fine structure (EXAFS). In the vacuum ultraviolet (VUV), studies on surfaces require auxiliary devices for electron spectrometry and LEED, while studies in molecular spectroscopy and photochemistry at these wavelengths may entail the use as ancillaries of mass spectrometers and of secondary photon detectors with time and energy sensitive response. Most of the experimental lines will depend on a computer system for control and data acquisition. There is a considerable expertise in this area in the Instrumentation Division at Brookhaven; the Division has in fact completed a study for a computer system planned for the needs of this facility (Informal Report, BNL 21109, April 1976).

Another factor to be considered is that the instrumentation employed in research with synchrotron radiation is becoming increasingly sophisticated and powerful. It is to be expected that the BNL facility will participate in this technical advancement, some of which can be anticipated. For example, deposited layered structures should find certain applications in x-ray monochromatization; holographic and microcircuit-like gratings will be widely employed in the ultraviolet for this same purpose. As their development proceeds, area detectors should come into their own for several types of x-ray diffraction; and video photon detectors, especially when their resolution is improved over the current 20 μm , should be useful in topography and perhaps in diffraction also. There are some problem areas in technique, however, in which the need for advance is at present clearer than the direction to be taken in achieving it. Faster, energy-sensitive photon detectors than those now available are needed, both for spectroscopy and for simply sorting out unwanted higher order wavelengths present in beams from some monochromators.

The full instrumentation budget - project, R&D, and capital - is intended not only to provide for initial testing and experimentation but also to furnish the base of equipment and of instrumental technique on which the national program of the facility will rely. There are to be eight fully equipped beam lines and several lines instrumented at least to include monochromators so that they could be completed soon after the facility is brought into operation. Although

some decisions about the particular classes of experiment these stations will serve and about details of instrumentation will be made later, as the time of utilization approaches, the nature of some parts of the installations can be anticipated. There will probably be at least one station for angular dependent photoemission spectroscopy, a diffraction station with an area detector and, of course, capacity for doing x-ray absorption spectroscopy. Complete stations will of course, be linked to computers. It is likely, on the 700 MeV ring, that for several lines it will be desired to place the first optical element, a mirror or grating, so close to the electron orbit that it will be located within the main ring vacuum enclosure. Such an installation obviously affects vacuum chamber and shielding design; it also presents problems in regard to avoidance of orbit perturbation caused by coupling between the electrons and discontinuities in the chamber walls. The coupling between ring design and beam line design mentioned at the start of this section is brought to light.

7. BUILDINGS AND UTILITIES

7.1 Introduction

The specialized properties of the synchrotron light source and of its research program set the requirements for buildings and services. The most significant of these are as follows:

- a. A very stable base for the storage rings and the optical beam lines. This is probably the single most critical technical requirement of the structure.
- b. An air temperature of about 75°F which must be maintained with small but reasonable variation to match the mean cooling water temperature.
- c. A controlled humidity level so that the dew point will always be well below the cooling water inlet temperature.
- d. Components are of small unit weight. This affects the design of the base and material handling methods.
- e. The electrical power demand is relatively small.
- f. Control of cooling water temperature is to be maintained for thermal stability of the storage rings.
- g. Beam lines and research apparatus are of small size and weight with low power and cooling water demands.
- h. Vibration must be minimized by separating rotating machinery from the ring building.
- i. Attached auxiliary space is to be provided for control rooms, laboratories and offices.

These requirements can be well satisfied by a modular, prefabricated or "pre-engineered" industrial type structure erected on a thick reinforced concrete slab. The area inside the storage rings will hold the injector and auxiliary, mostly electrical, equipment. Corners of the rectangular structure will be utilized for some long beam lines, staging areas for experiments, and storage of equipment not in service. Ductwork and primary services will be suspended overhead from the beams and purlins. Since ring parts and shield blocks will weigh no more than 4000 lb. each, they can be handled by standard floor-running equipment. The close packed array of experimental beam lines will limit access to some floor areas and possibly inhibit the approach to shield blocks from outside the ring. For this reason a study will be undertaken to provide either some local material-handling equipment or overhead-crane service.

A wing of ~10,000 sf is the minimum area that will house the control rooms, laboratories and some offices. Additional laboratory and office space will be provided in the existing buildings of the Accelerator, Biology, Chemistry and Physics Departments. An industrial type of structure on a separate foundation will house all rotating service machinery.

7.2 Site

The site proposed for the Synchrotron Light Source is on Technology Street, south of the building that houses the Instrumentation Division. It is reasonably level and has close access to the various services and utilities. It is across the street from the Physics Department and is a few minutes walk from the Chemistry Department and the Biology Department. The proposed location is shown in Fig. 7-1 on which are also shown Buildings 535 (Instrumentation), 510 (Physics), and 515 (Applied Mathematics).

7.3 Foundation Base

The overburden will be scraped away to compacted sand. A thick reinforced concrete slab will be placed in a pour without trenches. This concrete membrane will smooth small irregularities and spread the loads. Long span stability (greater than 10 to 20 ft.), is provided by the sand. The glacially compacted sand underlying Brookhaven National Laboratory has proved to be a stable and predictable base. If loads are kept below a few thousand psf, preferably below 3000 psf, the sand behaves like an elastic medium with some hysteresis. There are no indications of heaving or quasi-liquid behavior. The soil mechanics properties have been measured to high accuracy at the AGS which is near the proposed site. A check will be made to verify that soil conditions are similar.

Loading over an appreciable area gives a prompt settlement of 80 mils per 1000 psf with a rebound of about 2/3 that when the load is removed. The reloading curve is parallel to the rebound curve. Most of the loads imposed by this facility will produce deflections of a few mils. The 2.5 GeV ring shielding will weigh about 5000 to 6000 lb. per circumferential foot. If a short section of this shielding is removed for maintenance or development, the ring will rebound 10 to 25 mils (depending on length of the sector), but will recover to within a few mils when the shielding is replaced for operation. The only alignment problem anticipated could come from a heavy snow

FIGURE 7-1
PLOT PLAN

load. Once every few years the snow load on the roof will approach or exceed 10 psf. Forces transmitted through the columns could then disturb the ring alignment and interfere with operation until the snow is melted or removed. Removal of the load will restore alignment well within the range of the correcting coils. Since such a heavy storm would disrupt operation anyway, there is no justification for incurring the heavy expense of incorporating a long span roof structure to avoid this problem.

Years of experience with the AGS indicate that realignment of the rings will be required only at long intervals. Heavy loads in this facility will seldom be shifted. After a year or two from pouring the concrete, the annual temperature cycling beneath the slab will be very small. Provision for alignment of ring elements will be made by casting pipes in the internal shield wall for access by alignment tools. The rings can then be aligned to high precision with radius tapes, templates and optical levels.

7.4 Structure

The most economical structure is a pre-engineered shell with modules about 25 by 50 ft. The locations of support columns have been taken into account in the machine design and do not offer serious obstructions. Panels for sidewalls and roofs will be well insulated and a thick impervious mat will insulate the slab edge from the grade beam. These structures will be ordered complete with conventional HVAC, sprinklers, lighting, partitions, doors, toilets, etc. An eave height of 20 ft. will give about 17.5 ft. net clearance under the eave and about 25 ft. clearance at the ridge. The office and laboratory wing will be attached to the sides of the ring housing, and will be furnished with interior partitions and acoustical hung ceilings. The accelerator building will have a sheet metal sidewall liner but the roof steel will be left exposed so that services can be suspended from it. Some structural details are shown in Fig. 7-2.

A mechanical equipment building of about 5000 sf will be erected on a separate foundation to minimize vibration in the main slab. This building will contain the chillers, pumps, heat exchangers and compressors. Adjacent to it will be located the substations and evaporative coolers.

SECTION THROUGH BUILDING SHOWING TYPICAL CLEARANCE AT 2.5 GeV RING
Figure 7-2

7.5 Power

The peak demand is estimated as follows:

Magnet systems	1700 kw
Rf systems	1100
Small ring systems	100
Research apparatus	200
Mechanical services and building	1000
Peak demand	<u>4100 kw</u>

The incoming feeder will be 13.8 kv, 3-phase, and 10 Mva. Major rf power supplies using about 1000 kw will be supplied at 13.8 kv. The other loads will be supplied by two 13.8 kv/480 v, 3-phase 2500 kva unit substations packaged with load disconnect and secondary breakers. Heavy bus duct feeders will route to distribution centers in the rings and in the mechanical equipment building. Each distribution center will contain a 100 kva 480/120-208 v transformer for low power apparatus. An additional 120/208 v transformer will be located in the laboratory wing for power and lighting. Power for experiments will be distributed in bus duct hung on the outer periphery of the ring and shielding. Figure 7-3 is a one-line diagram of the proposed power system.

7.6 Cooling

Evaporative coolers will supply water through a closed circuit to the high power rf system, the chiller condensers and the HVAC condensers. Total peak demand, divided among four units, will be about 9 million Btu/hr. The dew point during much of summer is too high for cooling the magnet systems and vacuum chambers. For this reason about 600 T of chillers will be installed to provide a mean temperature of 75°F and rise of 15-18°F. When the dew point is sufficiently low, control valves will divert load from the chillers to the evaporative coolers. Demineralizers will be provided in the closed water circuits to maintain a high degree of water purity. Major supply and return piping will be routed to a few distribution points from which prefabricated manifolds will feed the multiple cooling connections (See Fig. 7-4).

7.7 Material Handling

Unit parts of the rings and shielding will be kept to about 4000 lb. maximum. These parts can then be handled by a telescoping hydraulic boom crane

PROPOSED ELECTRIC POWER SCHEMATIC

Figure 7-3

PROPOSED MECHANICAL SCHEMATIC

Figure 7-4

operating on the slab. A fork lift will be captive inside the 2.5 GeV ring for materials transfer to the boom crane. Sectors will be kept clear of long beam lines to provide access, and a number of overhead monorails will be mounted as auxiliaries. Limiting overhead crane coverage permits free use of vertical space for service risers and elimination of trenches in the slab. This not only reduces cost but also improves the stability of the slab, which was mentioned earlier as the most stringent structural requirement. Extensive material handling will not often be required during operation of this facility. The beam lines and experimental equipment are light in weight and will be installed with normal laboratory handling equipment.

8. COST ESTIMATES AND PROJECT SCHEDULES

8.1 Construction Schedule

The design, procurement, and construction schedule for this project is shown on the following page.

Construction of the facility covers a period of three and a half years, including a six-month run-in period before the machine is ready to support an experimental program. To meet this schedule some preliminary and accompanying support work is required (see Section 8.4). If authorization is granted for construction at the beginning of FY 1978, the experimental program can begin in April 1981.

The preparatory work necessary is to make possible placing orders of critical path and long delivery items immediately upon authorization. This includes buildings, magnets, vacuum components and other major construction items.

8.2 Manpower

The project manpower requirements are shown in Table 8.1. The estimate is given by fiscal year and is broken down into two broad categories; professionals (scientists and engineers), and non-professionals (technicians, draftsmen, and others). The totals estimated are 134 man-years (64 professional and 70 non-professional) for ED&I and 83 man-years (non-professional) for assembly and machine shop manpower associated with the storage rings and associated equipment. This estimate does not cover research and development activities, which are discussed in Section 8.4.

8.3 Cost Estimate

Details of the cost estimate are presented in summary Table 8.2 and in the detailed breakdown of Table 8.3. The estimate is based on current costs for labor and materials, with contingency and escalation amounts added as described below. The schedule of fiscal year obligations is shown in Table 8.4. An analysis of escalation and contingency amounts and the details of the total obligation flow are given in Table 8.5.

8.3.1 Site, buildings, and utilities:

The building estimate is based on the "pre-engineered" type structure described in Section 7. The cost estimates are based on quotes from several fabricators; utility estimates are based on Brookhaven experience.

Commitment Authority
▽

		1st Year	2nd Year	3rd Year	
STRUCTURE	Specify	Purchase	Construct		
ELECTRICAL	Specify	Purchase Substations, etc.	Install		
COOLING	Specify	Purchase Hx, Coolers, etc.	Install		
SHIELDING		Plumbing Contract			
MATERIAL HANDLING			Procure	Fabricate & Install as Req'd.	
LINAC		Acquire	Order Gun, Recondition	Install, Test	
BOOSTER					
MAGNETS	Design & Specify	Procure	Fabricate, Calibrate	Package	Install
POWER SUPPLIES			Procure, Fabricate & Test		Install
AUXILIARIES			Design, Procure, Fabricate		Install
VACUUM			Design	Procure & Test	Install
RF CAVITY			Design	Fabricate	Install
STORAGE RINGS					
MAGNETS	Design & Specify	Procure	Fabricate	Calibrate Package	Install SR
POWER SUPPLIES			Procure, Fabricate, Test	Install	SR
VACUUM	Study	Design	Fabricate	Test	Install SR
RF CAVITIES		Design	Fabricate, Test	Install	SR
RF AMPLIFIERS		Procure	Fabricate, Test	Booster	Install SR
AUXILIARY & SMALL ELECTRONICS			Design, Procure, Fabricate		Install SR
CONTROLS	Plan	Prototype, Test	Procure, Fabricate	Test	Booster SR
TRANSPORT		Study	Program		Small Ring Large Ring
VACUUM		Design	Procure, Fabricate		
MAGNETS		Design	Procure		
KICKERS	Study	Design	Procure, Fabricate		
WIGGLERS	Prototype		Design	Fabricate	Test
SYSTEM TEST				Procure Cryogenics	
				Linac-Booster	
					Small Ring
					Large Ring

LR - Large Ring
SR - Small Ring

SYNCHROTRON RADIATION RESEARCH FACILITY
PRELIMINARY CONSTRUCTION SCHEDULE

8.3.2 Storage rings and associated equipment:

The estimates for components of the storage ring facility and its auxiliaries are based on Brookhaven's extensive experience with similar components during the construction of two major accelerators. Where possible, estimates have been obtained from vendors.

8.3.3 Engineering, design, and inspection:

This estimate is based on the manpower schedule shown in Table 8.1 and on salary levels similar to those currently in use in Brookhaven's Accelerator Department, plus the Laboratory's current benefit costs. The total amounts to approximately 25% of construction costs.

8.3.4 Contingencies:

Based on BNL's experience and comparisons with other construction projects, contingencies are estimated at approximately:

- 15% on building and utilities
- 25% on storage rings and associated equipment
- 15% on ED & I and other manpower

8.3.5 Escalation:

The escalation estimates are based on the assumption that "in-house" manpower costs will escalate at a 6% rate per year and that building and apparatus costs will rise at 8% per year. The escalation rates are applied to the anticipated obligation flow during each year, with the assumption that the project will be funded in FY 1978. Construction cost obligations are expected to be complete by the end of the first quarter of FY 1980. Details of the escalation calculations are shown in Table 8.5.

8.4 Research and Development

This facility will serve a broad range of interest in various ERDA programs, as well as an extensive outside user community from university and industrial laboratories. During the conceptual design phase, therefore, the project has profited greatly from efforts and technical data from various sources having long-term interests in the facility. Continuing research and development work is expected to require operating expenditures as follows:

(in thousands)

FY 1977	\$ 500
FY 1978	500
FY 1979	500
FY 1980	400
FY 1981	400

The broad purpose of this effort initially will be to follow up the work accomplished in conceptual design with more definitive examination of key components of the project so that detailed design and facility construction can proceed as efficiently as possible. This supporting activity will be of critical importance, especially in FY 1977 and FY 1978, for meeting the project schedule. Work in the later stage will turn more to a program of development of new and specialized experimental apparatus for use on the beam lines.

8.5 Facility Operation

Estimated annual costs associated with the operation of the proposed facility and the BNL in-house research programs are summarized below. Amounts shown in FY 1976 dollars, would cover the first year of operations with 10 eight-hour shifts per week scheduled for research during this initial period, plus an allowance for maintenance, machine physics, etc. It is planned to activate eight beam lines during this first operating year; a staged development for several subsequent years will involve activation of additional beam lines with an accompanying expansion of research programs. Over a five-year period, the budget is expected to rise by about 35% (in unescalated dollars), with a major portion of the increase identified with the research budget component. Facility operating costs encompass those expenses for experimental area operations, equipment and machine development, and technical support for users, as well as costs associated directly with operation and maintenance of the machine itself. Capital costs are for equipment for both BNL and outside users. In order to have equipment ready for experiments at the eight beam lines, this level of equipment funding will be required beginning two years prior to operation of the facility.

The cost estimate is given in FY 1976 dollars because of the uncertainties of inflation factors, especially for electric power rates and prices of materials and supplies.

		<u>Cost in Thousands</u>
Facility Operations		\$ 2,100
Direct Manpower, including benefits (18 Professional, 24 Non-professional)	\$ 920	
Materials, supplies and supporting services	305	
Electric Power (15,000 MW hrs. @ \$26/MW hr.)	390	
General and Administrative	485	
Research Program.....		1,230
Direct Manpower, including benefits (17 Professional, 8 Non-professional)	605	
Materials, supplies, and supporting services	290	
General and Administrative	335	
Total Operating Costs.....		\$ 3,330
Capital Equipment.....		800

Research programs at the facility will encompass several scientific disciplines. It is anticipated at this time that BNL utilization of the facility will include programs in Materials Sciences, Molecular Sciences, and Biomedical and Environmental Research in approximate percentages of 55, 30, and 15 respectively.

TABLE 8.1

PERSONNEL ESTIMATE

(Man-Years)

	<u>Fiscal Year</u>				<u>Total</u>
	<u>1978</u>	<u>1979</u>	<u>1980</u>	<u>1981</u>	
<u>ED & I</u>					
Professional:					
Physicists	4.5	5	5	2.5	
Mechanical Engineers	3	3	3	1	
Electrical Engineers	3	4	4	1	
Vacuum Engineers	2	2	2	1	
Control Engineers	2	2	2	1	
Cryogenic Engineers	1	1	1	0.5	
Civil Engineers	1	-	-	-	
Administration	<u>1.5</u>	<u>2</u>	<u>2</u>	<u>1</u>	<u> </u>
Total Professional	18	19	19	8	64
Non-Professional	<u>15</u>	<u>24</u>	<u>24</u>	<u>7</u>	<u>70</u>
Total ED & I	33	43	43	15	134
<u>Assembly & Machine Shop</u> (Non-professional)	4	26	34	19	83

TABLE 8.2

SUMMARY COST ESTIMATE

(Thousands of Dollars)

<u>Schedule A:</u>	Buildings and Utilities	4,040
	Improvement to land.....	100
	Utilities.....	885
	Construction.....	2580
	Equipment.....	475
 <u>Schedule B:</u>	 Storage Rings and Associated Equipment	 9,540
	2.5-GeV Storage Ring.....	3565
	700-MeV Storage Ring.....	1215
	Injector System.....	980
	Associated Equipment.....	1980
	Experimental Equipment.....	1800
 <u>Schedule C:</u>	 E, D, & I	 3,400
 <u>Schedule D:</u>	 Contingency	 3,340
 <u>Schedule E:</u>	 Escalation	 3,680
	 T O T A L	 24,000

TABLE 8.3

DETAILED COST ESTIMATE
(In Thousands of Dollars)

<u>Schedule A:</u>	Building and Utilities.....	4,040
1.	<u>Improvement to land</u>	100
	Preparation, grading, seeding	58
	Paving, curbs	42
2.	<u>Utilities</u>	885
	Steam Service (L.S.)	45
	Water Service (150 ft. @ \$100)	15
	Sanitary Sewer (100 ft. @ \$50)	5
	Telephone (L.S.)	3
	Storm Sewer (1,800 ft. @ \$25)	45
	Fire Alarm (L.S.)	2
	Electric Utilities (L.S.)	115
	Special Power (L.S.)	150
	Trays and Special Conduit (L.S.)	75
	Machine Cooling (L.S.)	430
3.	<u>Construction</u>	2,580
	Main Building (62,000 SF)	1990
	Office-Lab Wing (10,000 SF)	400
	Mechanical Equipment House (5,000 SF)	190
4.	<u>Equipment</u>	475
	Laboratory Furniture	200
	Materials Handling Equipment	125
	Machine and Optical Tools	150

TABLE 8.3 (Continued)

DETAILED COST ESTIMATE

(In Thousands of Dollars)

<u>Schedule B:</u>	Storage Rings and Associated Equipment	9,540
1.	<u>2.5-GeV Storage Ring</u>	3565
	Ring Magnet System	1100
	Magnet Power	270
	Vacuum System	1060
	Transport, Inflection & Bump Coils	190
	Low Level Electronics	210
	Rf System	735
2.	<u>700-MeV Storage Ring</u>	1215
	Ring Magnet System	365
	Magnet Power	120
	Vacuum System	330
	Transport, Inflection & Bump Coils	145
	Low Level Electronics	140
	Rf System	115
3.	<u>Injector System</u>	980
	Reconditioned Linac	215
	Ring Magnet System	270
	Magnet Power	115
	Vacuum System	75
	Transport and Inflection	50
	Low Level Electronics	90
	Rf System	40
	Extraction	125
4.	<u>Associated Equipment</u>	1980
	Controls	740
	Wigglers and Associated Cryogenics	800
	Special Wigglers	300
	Shielding	140

TABLE 8.3 (Continued)

DETAILED COST ESTIMATE

(In Thousands of Dollars)

5. <u>Experimental Equipment</u>	1800
Detectors and Spectrometers	430
Monochromators: normal and grazing incidence, and crystal	440
Experimental Data Acquisition and Control	480
General Optical Equipment	50
Beamline and Station Mounts, Vacuum Equipment, and Local Shielding	400
<u>Schedule C:</u> Engineering, Design and Inspection	
134 man-years.....	3,400
<u>Schedule D:</u> Contingency.....	3,340
Buildings and Utilities @ 15%	605
Storage Rings and Auxiliaries @ 25%	2010
E, D, & I and Other Manpower @ 15%	725
<u>Schedule E:</u> Escalation.....	3,680
Buildings and Utilities	670
Storage Rings and Auxiliaries	1755
E, D, & I and Other Manpower	1255
 T O T A L	 24,000

TABLE 8.4

Brookhaven National Laboratory

Project No. 78-CH-004

National Synchrotron Light Source
Schedule of Obligations (in Thousands)

	<u>FY1978</u>	<u>FY1979</u>	<u>FY1980</u>	<u>FY1981</u>	<u>Total Project</u>	
					<u>Item</u>	<u>Total</u>
A. Engineering, Design and Inspection Costs	\$ 850	\$1,080	\$1,080	\$ 390		\$ 3,400
B. Construction Costs						13,105
1. Improvements to Land	100				100	
2. Accelerator Building	1,990				1,990	
3. Attached Laboratory Wing	300	100			400	
4. Mechanical Equipment Area	190				190	
5. Machine Cooling	190	150	90		430	
6. Utilities	255	200			455	
7. Special Facilities	3,600	3,800	1,800	340	9,540	
C. Standard Equipment						475
1. Laboratory Furniture and Equipment		100	100		200	
2. Materials Handling Equipment			125		125	
3. Machine and Optical Tools		130	20		150	
Sub-Total	\$7,475	\$5,560	\$3,215	\$ 730		\$16,980
D. Contingency on Above Obligations	1,470	1,160	600	110		3,340
E. Cost Escalation	1,070	1,380	950	280		3,680
Total Project Obligations	\$10,015	\$8,100	\$4,765	\$1,120		\$24,000
Appropriations Requested	\$11,000	\$9,000	\$4,000	---		

TABLE 8.5

NATIONAL SYNCHROTRON LIGHT SOURCE
 ESCALATION, CONTINGENCY, AND OBLIGATION FLOW ANALYSIS

	<u>FY1978</u>	<u>FY1979</u>	<u>FY1980</u>	<u>FY1981</u>	<u>Total</u>
I. Escalation Factors					
Manpower at 6%/yr from Jan. 1977	0.12	0.19	0.26	0.34	
All other costs at 8%/yr from Jan. 1977 through 1st qtr. of FY1980	0.12	0.21	0.24		
II. Base Estimate, Contingency, and Escalation Analysis					
A. Engineering, Design, and Inspection					
Manpower Costs	850	1,080	1,080	390	3,400
Contingency at 15%	<u>125</u>	<u>160</u>	<u>160</u>	<u>60</u>	<u>505</u>
Sub-total	975	1,240	1,240	450	3,905
Escalation at 6%/yr	115	240	320	150	825
B. Construction and Standard Equipment					
1. Buildings, Utilities, and Standard Equipment	3,025	680	335		4,040
Contingency at 15%	<u>455</u>	<u>100</u>	<u>50</u>		<u>605</u>
Sub-total	3,480	780	385		4,645
Escalation at 8%/yr	415	165	90		670
2. Special Facilities					
Assembly and Machine-shop Manpower	70	475	615	340	1,500
All other costs	<u>3,530</u>	<u>3,325</u>	<u>1,185</u>		<u>8,040</u>
Sub-total	3,600	3,800	1,800	340	9,540
Manpower contingency at 15%	10	70	90	50	220
Facility contingency at 25%	880	830	300		2,010
Manpower escalation at 6%/yr	10	105	185	130	430
Other escalation at 8%/yr	530	870	355		1,755
III. Obligation Flow					
Base Estimate	7,475	5,560	3,215	730	16,980
Contingency	1,470	1,160	600	110	3,340
Escalation	<u>1,070</u>	<u>1,380</u>	<u>950</u>	<u>280</u>	<u>3,680</u>
Total Obligations	10,015	8,100	4,765	1,120	24,000

Brookhaven National Laboratory
Associated Universities, Inc.
Upton, New York 11973

ENVIRONMENTAL ASSESSMENT

The Construction and Operation of the
National Synchrotron Light Source

1. Project Description

In this environmental assessment the action being considered is the construction and operation of an electron storage ring facility for the specific purpose of producing high intensity synchrotron radiation. Essentially the facility consists of two storage rings, the larger (2.5 GeV) of which is 43 meters in mean diameter and is designed for the production and use of x-rays. The small ring (700 MeV), 14 meters in mean diameter, will supply radiation in the vacuum ultraviolet (VUV).

Principal features of this facility are the beam containment in the form of a sealed annulus, an RF system for accelerating the electrons, magnets for collimating and bending the beam and an ultra-high vacuum system. An injector system comprising a 50 MeV Linac and a 700 MeV booster synchrotron is necessary. The requirement for extreme dimensional stability is met by supporting the rings on a monolithic reinforced concrete floor.

Temperature control is maintained by exhausting waste heat through the use of evaporative coolers or chillers depending on the climatic conditions prevailing when the facility is in use.

The project also includes construction of a new building to house the storage rings and associated experimental equipment, together with small laboratories, mechanical maintenance areas, and offices. The building will be of pre-engineered construction, one story high with approximately 62,000 square feet of gross floor area and about 1,400,000 cubic feet of volume. The insulated metal walls and the inner structural steel frame and roof columns will be supported on a reinforced concrete floor slab.

Although the design approach of this machine is new in many respects, construction involves only well-developed existing technology including the RF circuitry, vacuum systems and magnets.

2. Background

The overall Laboratory terrain is gently rolling, with elevation varying from 40 to 120 feet above sea level. The land lies on the western rim of the shallow Peconic River watershed, with the river itself rising in marshy areas in the north and eastern sections of the site.

The facility is proposed for construction in the central developed* area of the Laboratory site. The elevation of the proposed site is 85 feet above sea level and the groundwater level contour at this point is approximately 46 feet above the same datum.

The New York State Department of Parks and Recreation has advised that no registered historical sites of archeological interest are on record for the area occupied by BNL.

Background radiation levels have been measured continuously at BNL with respect to external gamma exposure and activity levels in air, water, soil, grass and milk. An extensive environmental monitoring and sampling program is conducted to ascertain any increment of pollutant levels within the regional ecological system which might be attributable to BNL effluents.

Routine BNL radioactive and chemical releases to the atmosphere, the Peconic River and the ground presently produce no perceptible impact on humans or biota; all such releases are well below applicable standard limits for off-site areas. Alterations of the physical environment by the addition of heat or ionizing radiation resulting from BNL operations have had no measurable impact on humans or other biota.

The perturbations in ground water levels due to BNL operations are minor and local in nature.

In an evaluation of the continuing effects of past BNL operation as documented in an environmental impact statement, ERDA-1540 dated November 1975 (draft), no perceptible impact on the off-site environment was found to exist.

* Present plans indicate that this facility will be located in the developed area of the Brookhaven site. If, based on further considerations, an alternative site, particularly on an undeveloped area of the Laboratory, is selected, further environmental analysis will be performed.

3. Anticipated Benefits

This facility will provide a capability for multidisciplinary research with synchrotron radiation in a range not presently available in the U.S. As a powerful investigative tool, it has great value in the materials, molecular, and life sciences. The facility has importance not only because of its value for fundamental research in these broad areas, but also because of its importance for experimental and diagnostic investigations directly relevant to practical energy and environmental concerns of the nation.

There are several characteristics of the synchrotron light emitted from an electron storage ring which make it uniquely useful to many classes of research. The spectrum is continuous, and the intensities achievable are exceptionally high. Further, beams are stable in position and intensity and are highly polarized. Photons are emitted in nanosecond width pulses with separations between pulses of a few tens of nanoseconds up to about a microsecond. This time structure can be exploited for the study of dynamical properties and kinetic processes.

4. Environmental Impacts

4.1 Construction

Since this proposed project involves the construction of a relatively simple building in the previously developed area of the Laboratory site, construction impacts are expected to be minimal. Inasmuch as building foundations have no deep penetration into the soil, the cutting and filling operations will not be significant, and there should be no problem with erosion and/or siltation. The substructures of the building will have no interaction with the water table, thereby precluding drainage and other hydrological problems. Noise levels generated during construction would not be expected to be significantly different from those associated with the construction of residential to light industrial structures.

The construction operation will require the removal and redistribution of approximately 13,800 cubic yards of soil. The construction of the building will be carried out with approximately 65,000 tons of steel and 2500 cubic yards of concrete. In addition, the fabrication of the experimental equipment and associated shielding will require approximately 200 tons of ferrous metals, 40 tons of copper, 20 tons of lead, less than 1 ton of aluminum and 800 cubic yards of concrete. Waste generated during construction will be disposed of in existing areas on

site, i.e., the land fill. Every effort will be made to reclaim building scraps. No impacts should arise from efforts to tie into existing utilities since they are already present in the general area in underground trenches and conduits.

During the course of construction of this project, approximately 60 workers will be employed for 3-1/2 years. The salaries generated, as well as equipment and supplies purchased, will have a beneficial effect on the economy of the neighboring communities.

4.2 Operation

a) Emissions

Direct radiation from this machine is not thought to have any significant adverse impacts in that it will be controlled to be well within occupational standards in the vicinity of the machine's experimental areas and therefore will have virtually no effect beyond the bounds of the building. The maximum total radiation exposures will result during accidental beam dumps and will be in the order of approximately 100 mrem at contact with the shielding. Activation of machine components and experimental equipment is not expected to be a significant problem. Likewise, production of tritium and activation of cooling water impurities will be minimal. The only other effluent to be considered is that of process water which will be discharged from its evaporation cooling system used to dissipate the waste heat from the facility. This low volume of water effluent which will be discharged to the sanitary sewage system as a result of blow down will contain small quantities of treatment chemicals typical of those already in use in other cooling systems at the Laboratory. The incremental burden of these materials on the sewer treatment plant is not expected to be of significance. Essentially all of the energy input to this machine will be ultimately given up as heat, primarily by the evaporation of water. This should have no significant atmospheric effects and in fact is only a small fraction of that amount of heat presently discharged by the HFBR cooling towers which apparently have no adverse off-site meteorological effects.

b) Existing Utilities

Inasmuch as the existing utility systems at the Laboratory have been designed with a considerable amount of latitude for additional development, the installation of the synchrotron radiation facility would not appear to significantly tax any of these facilities. Water and electrical requirements can be achieved by direct connection to existing underground lines in the

immediate vicinity of the facility and sanitary and other waste can be adequately handled by the sewage treatment plant which presently operates at approximately 60% of its designed load. As mentioned previously, the disposal of waste, radioactive and otherwise, can also be handled through existing systems.

c) Commitment of Resources

Water consumption will be minimized in this facility as a result of the use of a closed cycle heat removal system which is provided with secondary cooling by either evaporation or refrigeration (depending upon ambient dew point). The cooling system will consume water only as make-up for evaporation. This is projected to be approximately 150 gallons per minute, a small fraction of total Laboratory use.

The electric power required to operate the synchrotron radiation facility and experimental programs associated therewith is calculated to be approximately 1.5×10^7 kW hrs. per annum. This represents an increase of approximately 7.5% of the total present Laboratory consumption which is a small fraction of the regional electric use.

The only critical material which is used to any significant degree during synrad operation is helium which is employed in 1000 liter quantities. However, losses are minimized by a secondard containment system which enables the recovery of any helium which might otherwise escape.

d) Socio-Economic

Since this facility will be dedicated to user orientation, it will involve not only Laboratory employees but those from outside industry and universities and therefore will have a pronounced benefit to the Laboratory's relationship with these institutions. Employment during operation of the facility is estimated to be 54 people initially and to increase by approximately 35% in the first five years of operation.

In summary, it appears that, on the basis of this analysis, the construction and operation of this facility will not have significant adverse impacts on the environment.

5. Conflict with Other Plans and Programs

There are no known conflicts with federal, state, regional or local plans or programs. It is particularly important to note that since this facility is planned for construction on a developed area of the site, there will be no conflict with the NERP program through which ERDA is expected to use undeveloped areas of the site for ecological research.

6. Reasonably Available Alternatives

The several existing facilities dedicated solely to synchrotron radiation research are small and provide a spectra extending from the long wavelengths only to the far ultraviolet. Those machines that can furnish protons at x-ray wavelengths were designed and have been used mainly for high energy physics and have many shortcomings for synchrotron radiation utilization due to design characteristics and problems with operating conditions and scheduling. Moreover, many of these sources do not have the beam stabilities provided by a storage ring. For this reason there are no reasonably available alternatives in the United States.

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C. Albert	G. K. Green
R. G. Alsmiller [*]	L. A. Harson
M. Blume	B. M. Kincaid ^{**}
W. R. Casey	H. R. Manning
R. Chasman	W. H. Moore
L. C. Emma	M. L. Perlman
B. C. Frazer	E. J. Tuthill
J. B. Godel	R. E. Watson

^{*} Oak Ridge National Laboratory

^{**} Bell Laboratories