SSRP:

Stanford Synchrotron Radiation Project

The Stanford Synchrotron Radiation Project is a new national facility which makes use of the intense radiation produced by the SPEAR storage ring at SLAC to carry out important research in several fields of the physical and biological sciences. This article describes the SSRP facility and its early experimental program. It also gives some of the basic technical information needed to understand how the facility works and why its research program has already started to yield significant results.

Contents

A. INTRODUCTION

The Stanford Synchrotron Radiation Project (SSRP) is a new national facility for research in a variety of scientific disciplines, including physics, chemistry, biology, metallurgy and astrophysics. Although the Project is located at SLAC, adjacent to the SPEAR storage ring, it is funded by the National Science Foundation under a contract with the W. W. Hansen Laboratories of Physics on the Stanford campus. In addition to NSF support, contributions to the Project have been made by the U.S. Navy's Michelson Lab at China Lake, California; by Xerox Corporation; and by Bell Telephone Laboratories. The originators of SSRP are Professors Sebastian Doniach and William Spicer of Stanford (now the Director and Consulting Director, respectively), with much early help from SLAC's Gerry Fischer.

Experiments at SSRP make use of the intense synchrotron radiation that is given off as a "by-product" of the operation of the SPEAR

storage ring. This "free" radiation has several remarkable properties: (a) high intensity, (b) a broad range of energies including some that are difficult to produce at useful intensities by other means, (c) natural collimation, (d) high polarization, and (e) pulsed time structure. (More information on these properties is given later.) Perhaps most important is the intensity, which is so high that even a very narrow band of energies will contain enough flux for a great variety of experiments. Before turning to a description of SSRP itself, we now want to review, in Section B, some physics background.

B. SOME BACKGROUND INFORMATION

1. Light And Other Radiation

Most people at SLAC have heard about the comparison that is often made between an accelerator and a microscope. With a conventional microscope, which uses visible light, we can see objects such as parts of living cells that may be less than .001 centimeter (10^{-3} cm) long. By using a more powerful kind of light (x-rays or electrons which have energies of some thousands of volts), we can get a picture of some of the smallest living things, such as viruses, that may be only 10^{-6} cm in size. And usually the next step we talk about at SLAC is the great leap inward that takes us all the way down to the realm of the elementary particles, such as the proton, whose size is about 10^{-13} cm. To illuminate protons we make use of a special kind of 'light' that is actually a beam of electrons which has been accelerated to billions of volts by the SLAC two-mile accelerator. Thus the 'resolving power' of the SLAC accelerator is about 10^{10} times greater than that of a conventional light microscope.

2. Atoms, Molecules And Angstroms

But hold on a minute. When we jumped from viruses all the way down to protons, we skipped right over a whole class of objects--atoms and molecules--that are almost completely responsible for making the world the way it is. So this time let's go back for a closer look at what we missed. To begin with, we'll need a

new yardstick to give us a convenient unit of size for measuring atoms. This unit is called the *angstrom*. Its symbol is 'Å' and it is this big:

$$1 \text{ Å} = .00000001 \text{ centimeter} = 10^{-8} \text{ cm}$$

The angstrom is convenient* because it is close to the size of an atom: the radius of a hydrogen atom is about 0.5 Å, and the radius of a uranium atom is about 2.0 Å. Although those physicists who study the elementary particles have passed the atom by in their search for the smaller game that lives within the very small nuclei of atoms (about 10^{-4} Å, or 10,000 times smaller than the whole atom), it is worth remembering that the nucleus itself plays an almost totally insignificant role in the substance and activity of our everyday experience. But the whole atom, on the other hand, is definitely where it's at. It is because of the structure of atoms and their interactions with each other--and the tremendous variety of both --that steel is strong, water is wet, roses are red, and soap is slippery. In fact, it is because of atoms that almost everything is *any-thing*.

3. What 'Size' Light Do we Need?

Thus the realm of the atom and of the combinations of atoms that form molecules is the starting place for trying to understand any of the larger units of matter, both physical and biological, that occur in nature. In order to explore this realm successfully, we will need to select (as we did for viruses and for protons) just the right kind of light to shine on the atoms. The essential requirement is that the light be of a 'size' (wavelength) that matches the dimensions of the particular atomic or molecular structures we shall be studying. We can get an idea of the range of sizes that will be useful in this work by consulting Fig. 1, which shows some of the characteristics of electromagnetic radiation.

From this figure we see that the size of an atom, about 1 angstrom, is matched by radiation that lies in the x-ray region of the spectrum. For a wavelength of 1 Å, the corresponding x-ray energy is about 12,000 electron volts, or 12 keV. In order to study some of the inner electronic structure of atoms we will want to use x-rays that are somewhat 'harder' than 12 keV--say up to energies of 20 or 25 keV. In addition, structures up to several atoms in size will need 'softer' radiation from the ultraviolet portion of the spectrum. Ideally, then, our bag of radiation tricks should include the following range of energies and wavelengths:

---

*Metrication note: In the International System of units (SI), the preferred unit of length for the sizes we're talking about is the nanometer, which 10^{-9} meter, or 10 Å.

ELECTROMAGNETIC RADIATION

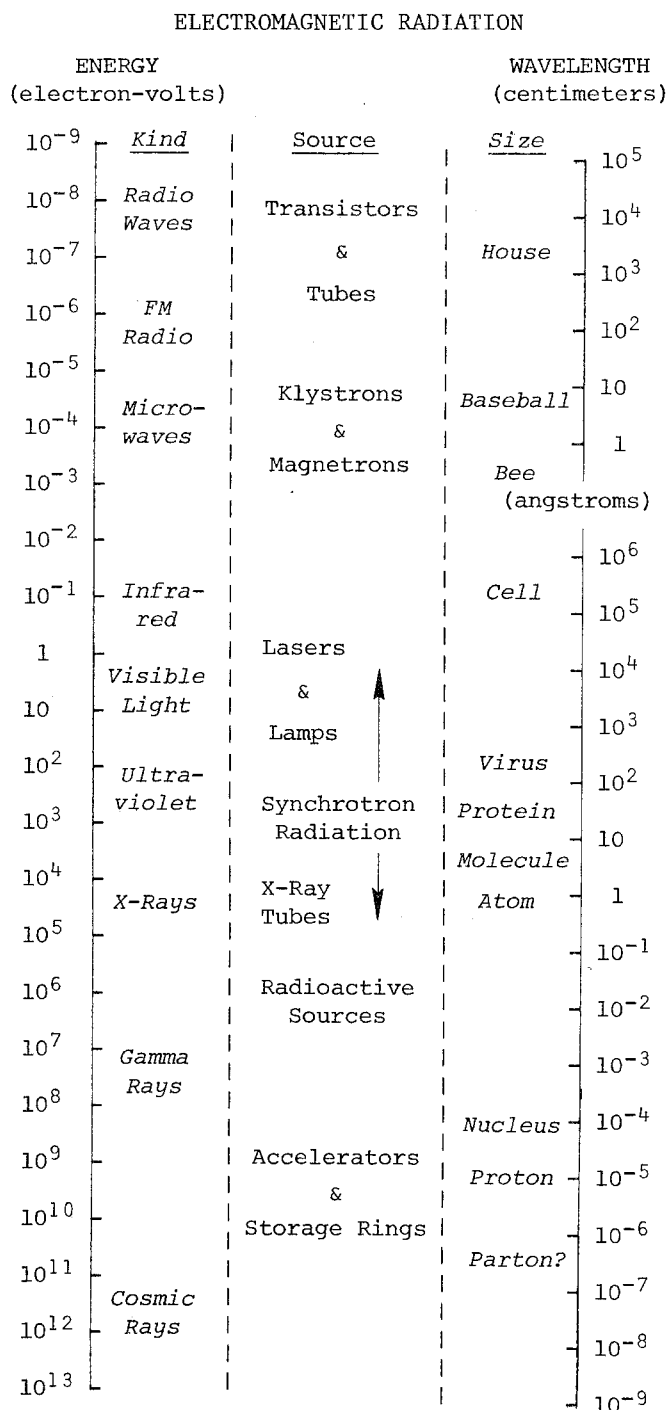| ENERGY (electron-volts)			WAVELENGTH (centimeters)
10^{-9} — Kind	| Source	| Size	
10^{-8} — Radio Waves	Transistors		10^5
10^{-7}	&	House	10^4
10^{-6} — FM Radio	Tubes		10^3
10^{-5}			10^2
10^{-4} — Micro-waves	Klystrons &	Baseball	10
10^{-3}	Magnetrons	Bee	1
10^{-2}		(angstroms)	
10^{-1} — Infra-red		Cell	10^6
1 — Visible	Lasers		10^5
10 — Light	& Lamps		10^4
10^2 — Ultra-violet		Virus	10^3
10^3	Synchrotron Radiation	Protein	10^2
10^4 — X-Rays	X-Ray Tubes	Molecule	10
10^5		Atom	1
10^6	Radioactive Sources		10^{-1}
10^7 — Gamma Rays			10^{-2}
10^8			10^{-3}
10^9	Accelerators	Nucleus	10^{-4}
10^{10}	&	Proton	10^{-5}
10^{11} — Cosmic	Storage Rings		10^{-6}
10^{12} — Rays		Parton?	10^{-7}
10^{13}			10^{-8}
			10^{-9}

Fig. 1--Part of the spectrum of electromagnetic radiation. Longer wavelengths, such as very low frequency radio waves, lie off the top of the scale. Very energetic gamma rays produced by cosmic radiation (energies greater than 10^{20} electron-volts!) lie off the bottom of the scale. Although there is a vast range shown here, all electromagnetic radiation is fundamentally the same (same velocity, for example). When this radiation is used to probe the structure of matter (cells, atoms, protons), the wavelength chosen should be as small as, or smaller than, the dimensions of the structure being probed.

Wavelength: 0.5 to 100 Å

Energy: 0.12 to 25 keV

4. Speaking In Colors

All electromagnetic radiation comes in dis-
crete "packets" or units called *photons*. We
have already seen that there is a simple inverse
relationship between the energy carried by a
photon and its "size" or wavelength: the higher
the energy, the shorter the wavelength. For the
very narrow band of radiation that human beings
can actually see (roughly between 4000 and
7000 Å), a change in wavelength or energy is
also seen as a change is color. To us, radia-
at 6500 Å is simply red light, while 4700 Å is
seen as blue light. Because of this, scientists
sometimes extend the idea of colors to describe
radiation even when they are referring to parts
of the electromagnetic spectrum that cannot
actually be seen. Thus ultraviolet radiation
is said to be *bluer* than visible light, and a
beam of gamma rays which all have the same energy
is sometimes described not only as *monoenergetic*
but also as *monochromatic* (all of the same
color). In general, then, the following rather
loose talk is used:

> *bluer = harder = higher energy*
> *redder = softer = lower energy*

Which is probably a good place to stop the loose
talk and get on with the subject at hand.
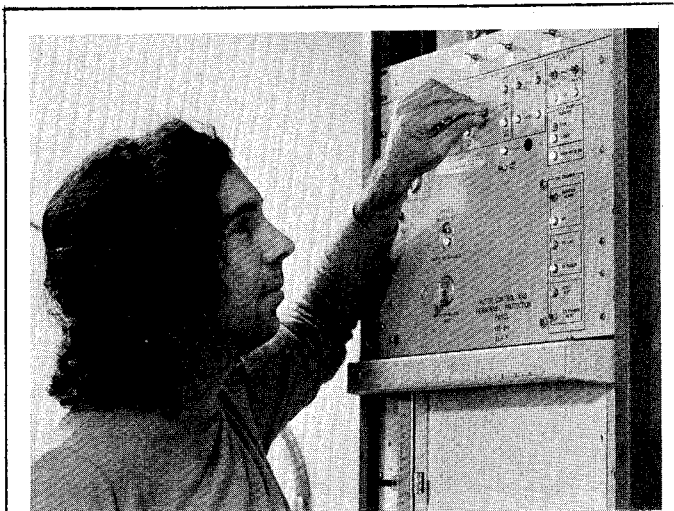
--Photo by Joe Faust

Visiting experimenter Steve Kowalzyk from
Lawrence Berkeley Lab is shown opening shutters
at the personnel protection control panel that
was designed by Bruce Humphrey of SLAC. Rad-
iation shielding, plus the gates, shutters and
radiation monitors controlled by this system
permit experimenters to control access to
their individual research areas in complete
safety, independent of the operation of SPEAR
and of other SSRP experiments.

C. THE SSRP FACILITY

We turn now to a discussion of the SSRP
facility itself, starting with the synchrotron
radiation produced by SPEAR. We then follow
this radiation from SPEAR into SSRP, describe the
SSRP layout, and finally call attention to some
of the special research apparatus at SSRP.

1. SPEAR's Rainbow Of Light

The SSRP facility is located at SPEAR in
order to take advantage of the intense radia-
tion that SPEAR gives off as a natural by-
product of its normal operation. This radia-
tion is caused by the fact that the electrons
traveling in a curved path around the SPEAR ring
lose a certain amount of their energy on each
revolution. The radiation from SPEAR is emit-
ted in the orbital plane of the electrons--
flying off from the circular beam path in much
the same way that mud flies off from a spinning
automobile tire. This kind of centrifugal or
"thrown-off" radiation is characteristic of the
class of accelerators called "electron synchro-
trons" (which includes SPEAR), and for this
reason it has been given the name *synchrotron
radiation*. For SLAC's purposes, the synchro-
tron radiation given off by SPEAR is more of a
nuisance than a benefit, as Fig. 2 illustrates.

	Energy Of One 20-milliampere Beam (GeV)	Radiation Loss (kilowatts)
SPEAR I	1.5	0.7
	2.0	2.2
	2.5	5.4
SPEAR II	3.0	11.2
	3.5	20.8
	4.0	36.0
	4.5	57.8
PEP	15	500

Fig. 2--Synchrotron radiation energy loss
at SPEAR and at (proposed) PEP. This synchro-
tron "mud" thrown off by the circulating beams
heats up the inner walls of the SPEAR vacuum
chamber and also knocks gas molecules out of
the chamber walls. Thus both a water-cooling
system and an elaborate vacuum-pumping system
are required. In addition, a strong radio-
frequency accelerating system is needed to
give the beam particles a carefully timed
"kick" on each revolution in order to make up
for the energy lost by synchrotron radiation.
These problems rapidly become more difficult
as the energy of the beams is increased. For
example, doubling the energy of one stored
beam in SPEAR results in a 16-fold increase
in the power lost to synchrotron radiation.

So synchrotron radiation is a natural by-product of the operation of SPEAR, and the next step in our investigation of SSRP is to find out a little more about this radiation—how many photons are given off per second, what energies do they carry, and so on. Information of this kind about a radiating source is called a *spectrum*. The spectrum of synchrotron radiation from SPEAR is shown in Fig. 3.
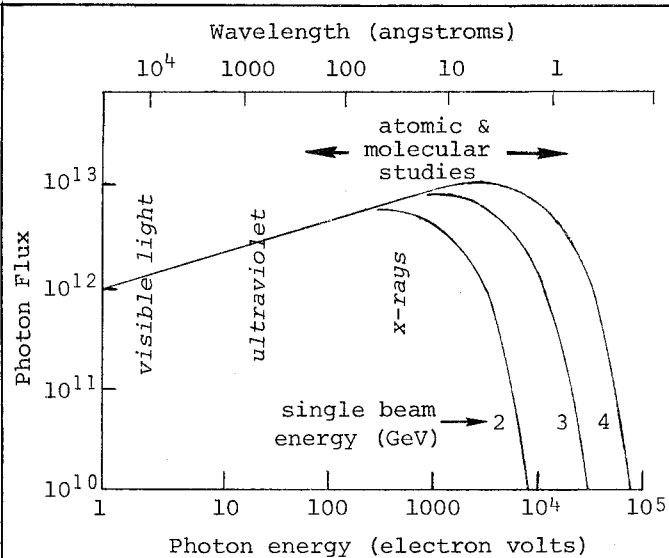
Fig. 3—The spectrum of electromagnetic radiation from the SPEAR electron beam at beam energies of 2, 3 and 4 GeV. The radiation intensity is at its peak in the region from 0.5 to 100 angstroms, which is an excellent match to the wavelengths needed for atomic and molecular studies. The vertical scale in the figure can be read simply as relative intensity. The actual numbers shown correspond (if you really care) to the following complicated units:

$$\frac{number~of~photons}{second\text{-}milliampere\text{-}milliradian\text{-}10\%~bandwidth}$$

2. *Some Practical Matters*

We now turn to the practical problem of how to get the synchrotron radiation out of the SPEAR ring and into the SSRP facility. What we need is an opening or porthole in the SPEAR vacuum chamber that will let the radiation come out, but will *not* let the air get in. This particular requirement—maintaining the 'vacuum integrity' of SPEAR—is the single most important technical consideration in joining SPEAR and SSRP together. If SPEAR is to run satisfactorally, it needs a vacuum of less than 10^{-8} Torr—a level about 20 times better than that of the two-mile accelerator. If the pressure is higher than that, the SPEAR beams bump into so many gas molecules that they get frittered away to low intensity (few particles) too quickly. Materials selection and surface preparation are important for such low vacuum levels.

The problem of getting the radiation out of SPEAR can be divided into two parts: (1) hard x-rays, with energies above about 3500 electron volts, and (2) all the rest of the lower energy x- and ultraviolet radiation. For the hard stuff, the solution is fairly simple. X-rays of 3.5 keV and higher will readily pass through a vacuum-tight 'window' which consists of a thin foil of beryllium metal. This window acts as a dependable barrier between SPEAR's good vacuum and the outside world. Once through the window, the hard x-rays continue in an atmosphere of helium to the experimental stations.

For the remaining, lower energy radiation, the solution that has been adopted is to extend SPEAR's vacuum system tangentially out in a 'finger' toward the SSRP facility (see next page). This extended vacuum system is potentially vulnerable to leaks that may occur in various pieces of SSRP experimental apparatus. For this reason, a special fast-acting vacuum
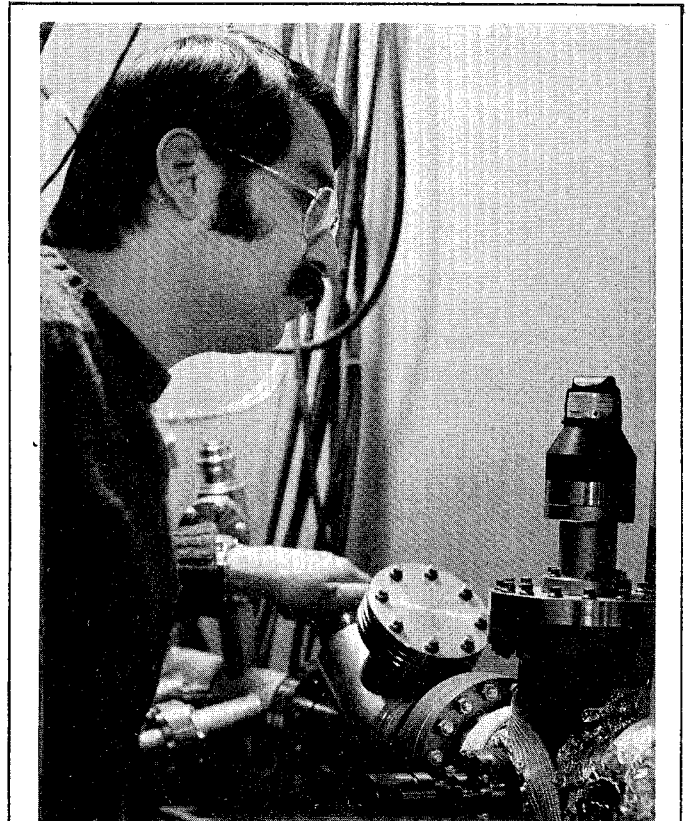
--Photo by Joe Faust

SSRP vacuum specialist Ralph Gaxiola is shown opening a high-vacuum valve on the 4° beam line at SSRP. Protection of the SPEAR vacuum and of the experimental vacuum systems is a prime concern of SSRP. Ralph gained much of his knowledge of ultra-high-vacuum systems while working in Norm Dean's SPEAR vacuum group. His responsibilities include interfacing with experimenters who want to connect their equipment into the extended SPEAR vacuum system.

valve (supplied by the CERN ISR group) has been
installed near the SPEAR end of the extended
finger. This valve can close in .03 second if
triggered by any of several ionization gauges
or other "gas sniffers" around the system.
Care has also been taken to avoid contaminating
either the SPEAR or SSRP systems with such mat-
erials as heavy hydrocarbons.

3. *The Layout Of SSRP*

The general arrangement of beams and exper-
imental apparatus in the SSRP facility is illus-
trated in Fig. 4. Inside the vacuum chamber
coming from SPEAR there are two special mirrors
which split the narrow spray of synchrotron rad-

iation into three separate beams: (1) The
straight-ahead undeflected beam consists of
hard x-rays with energies of 3.5 keV and above.
(2) A second beam is reflected sideways through
a 4° angle; it consists of ultraviolet and x-
radiation with energies less than about 2 keV.
(3) The third beam is reflected upward through
an 8° angle; it consists of the softer ultra-
violet radiation of 300 eV or less energy.

The straight-ahead, hard x-ray beam is sim-
ultaneously shared by three different experi-
mental areas. If the need should arise, more
elaborate switching and splitting systems can
be added to provide additional experimental
areas for any of the three main beams.
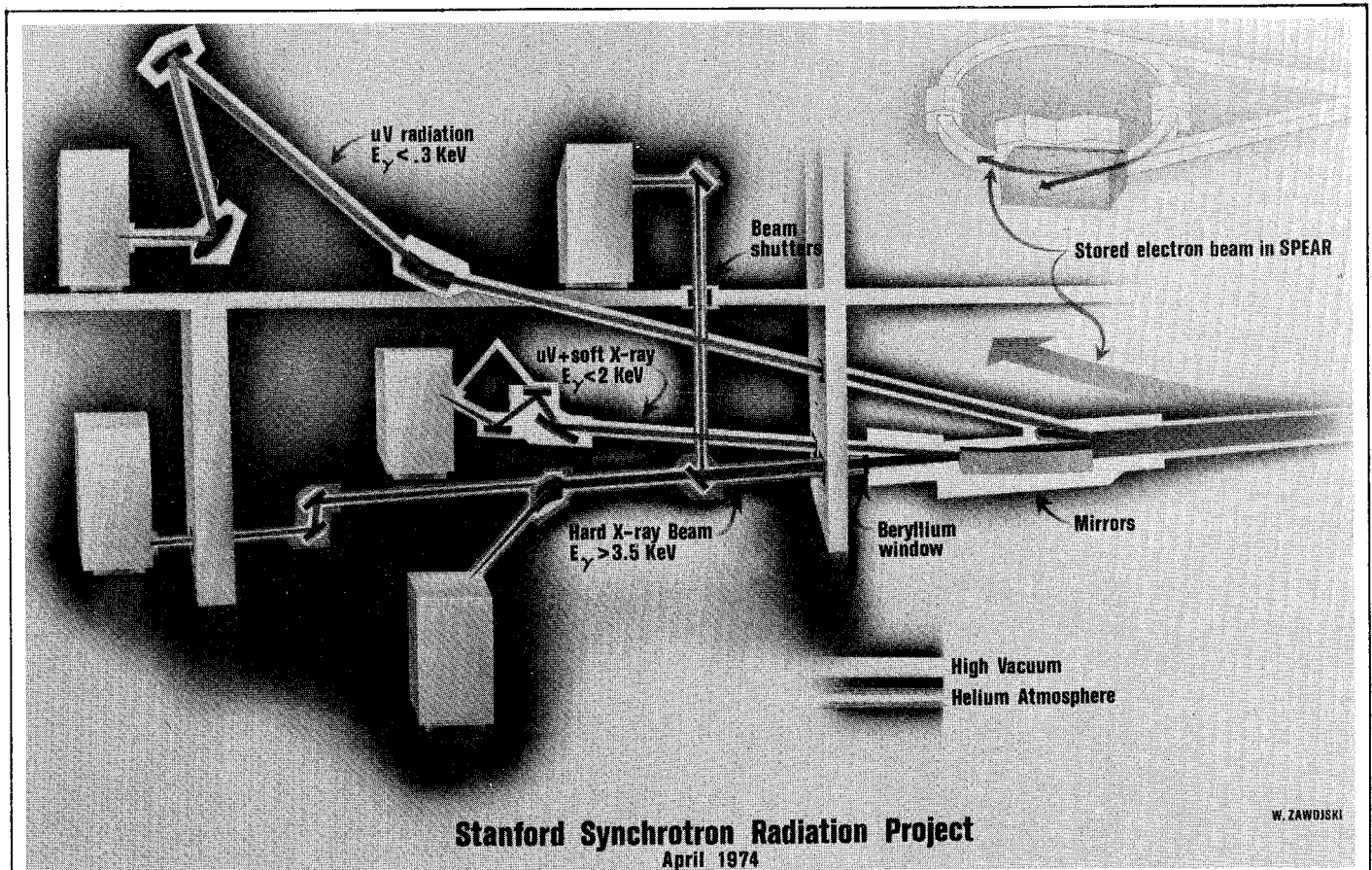

Stanford Synchrotron Radiation Project
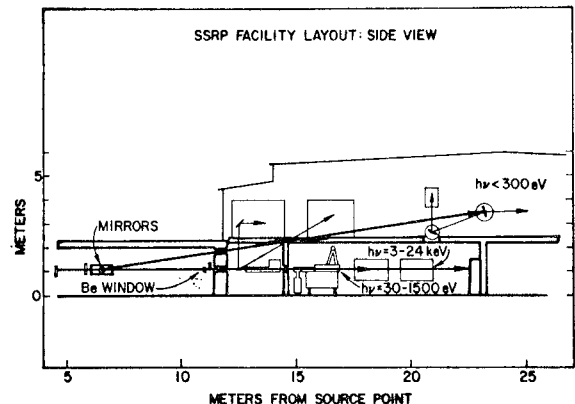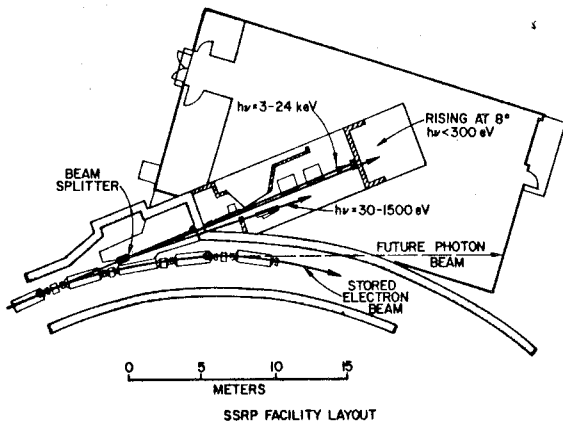April 1974

Fig. 4--SSRP Layout

The two beam-splitting mirrors at the front end of the SSRP beam system are particularly important and thus worth some special attention (see Fig. 5). Each is constructed of a thick copper block, polished to an exceptionally smooth finish, and plated with a thin layer of platinum. One of the mirrors is plane (flat), while the other has a very slightly concave cylindrical surface which focuses the radiation in the horizontal plane. The synchrotron radiation from SPEAR is sufficiently intense so that the mirrors must be able to dissipate something like 50 or 100 watts. Normally this heat load would be handled by a water-cooling system, but in this case it was decided that a rapid flow of water might cause a mechanical disturbance of the mirrors and thus affect the reflection of the synchrotron radiation beam. Since the alignment of of the beams is critical (they must be precisely directed to monochromator entrance slits that are only .001 centimeter wide), the cooling technique that has been adopted for the mirrors is the novel thermoelectric method.
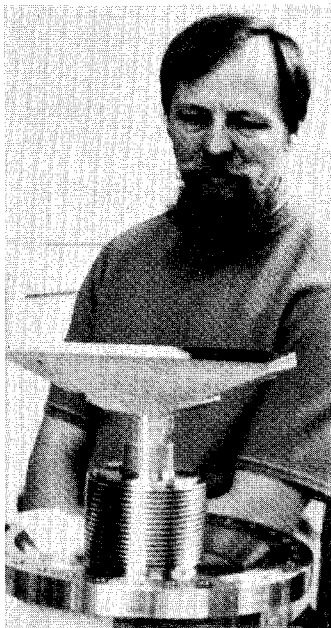
--Photo by Herm Winick

Fig.5--Vic Rehn of the U.S. Navy's Michelson Lab at China Lake, California, is shown with one of the two beam-splitting mirrors that are used to separate the synchrotron radiation from SPEAR into high-, medium- and low-energy components. Vic's group has pioneered in the design and construction of such ultra-smooth mirrors. The mirror shown here has an average surface roughness of less than 30 Å, and is probably the smoothest piece of metal of this size ever made. Two such mirrors are used at SSRP.

4. Monochromators

As we noted earlier *monochrome* means 'one color,' so a *monochromator* is a device for getting radiation of a single color (or energy or wavelength). Perhaps it will come as a surprise that you are already familiar with a monochromator of a certain kind: a prism. As a reminder, Fig. 6 shows how the combination of a prism and a slit can be used to select one color of radiation from a mixed bag of colors.
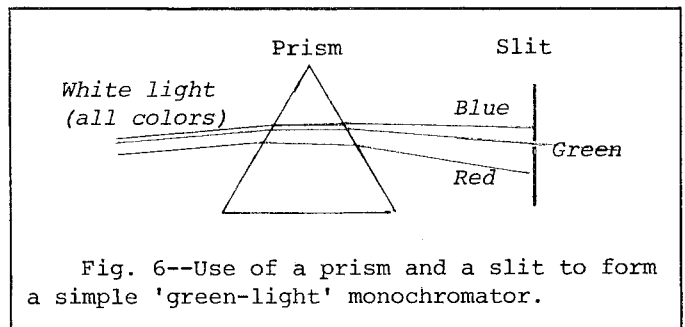
Fig. 6--Use of a prism and a slit to form a simple 'green-light' monochromator.

The fancier monochromators used at SSRP and elsewhere produce somewhat the same result as a prism, but they do it in a different way. The white light passing through a prism is spread out into its constituent colors by a process called *refraction*. This color separation can also be achieved by the *diffraction* of light from either of two kinds of special surfaces: (1) a man-made *diffraction grating*, or (2) any of a number of natural *crystal* materials. Let's look at these two monochromator possibilities in turn (next page).
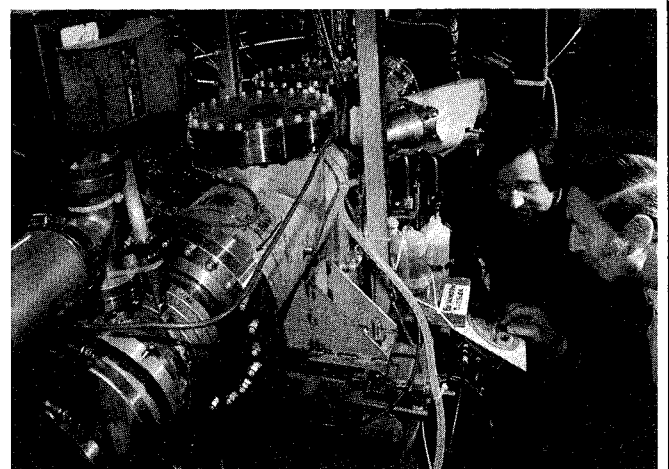
--Photo by Joe Faust

Ben Salsburg (left) and Axel Golde of the SSRP staff are shown checking the helium flow in the straight-ahead x-ray beam line. This view is taken looking back toward SPEAR. Axel is responsible for mechanical facilities at SSRP. He works with experimenters to fit their equipment into the appropriate beam line, and also designs shielding, helium systems, beam shutters, and other mechanical components.

Diffraction gratings. The original form of diffraction grating, devised by a man named Fraunhofer, consisted of a series of parallel wires spaced an equal distance apart, as shown in Fig. 7.
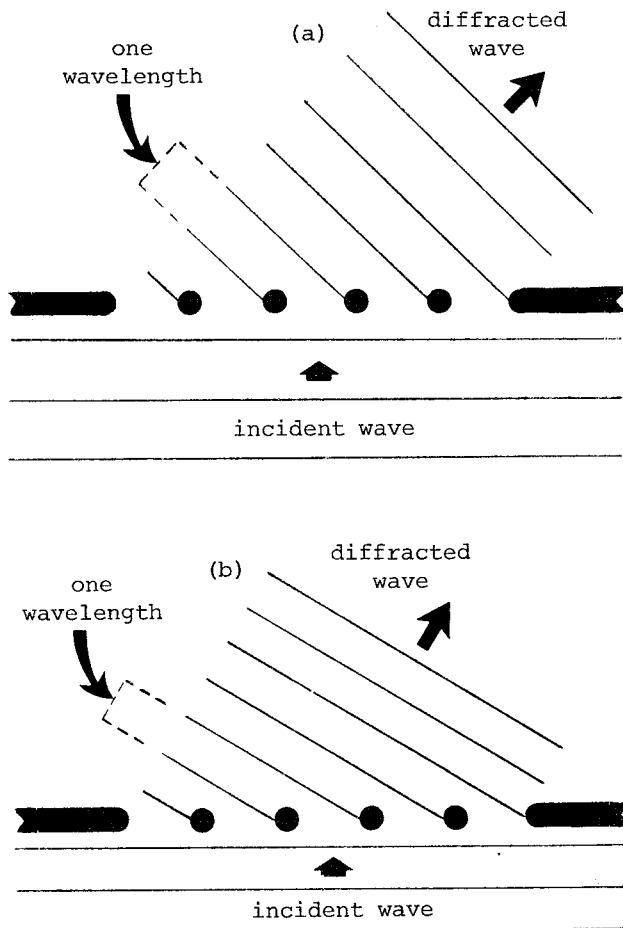

Fig. 7--A diffraction grating made of four parallel wires. The two sketches, (a) and (b) show how different wavelengths of radiation are diffracted at different angles by the wires. This is an example of a *transmission* grating, in which diffraction occurs as the radiation passes through the wire grid. The more common form, described in the text, is a *reflection* grating, in which the diffracted radiation reflects back from a grooved solid surface. All diffraction gratings serve the purpose of separating radiation into constituent 'colors' or wavelengths, and are thus the key elements in monochromators.

We used the parallel-wire form of diffraction grating to illustrate the principle because it is easy to draw. However, the more common form of grating is a smooth surface into which many parallel grooves have been cut by a sharp scribing instrument. Since the spacing between grooves (or wires) will determine the range of wavelengths that can be separated (or *dispersed*) by a grating, short wavelengths will require very close spacing. A machine called a 'ruling engine' is used to cut or scribe the grooves, and the most accurate of these machines can cut as many as several thousand grooves per centimeter on a suitable surface. If we recall, however, that our studies of atoms may require x-rays with wavelengths of less than a *millionth* of a centimeter, then it's obvious that even the best of man-made diffraction gratings will not be good enough, and we'll have to look elsewhere for a 'one-color-maker.'

Crystal monochromators. The ultimate diffraction gratings are those produced by nature. On the surface of such crystalline solids as quartz, for example, the regular spacing of the rows of atoms in the *crystal lattice* produces the same effect as the parallel grooves in a ruled grating. And since the distance between the parallel rows of atoms in a crystal is roughly a few angstroms, such crystals can be used to sort out x-ray wavelengths into their constituent 'colors.' As an example of the kind of resolution that can be achieved, there is a monochromator presently in use at SSRP which successively diffracts an x-ray beam from two separate crystals. This device yields an 8 keV x-ray beam in which the energies of the individual photons are the same to within about 0.2 electron-volts.
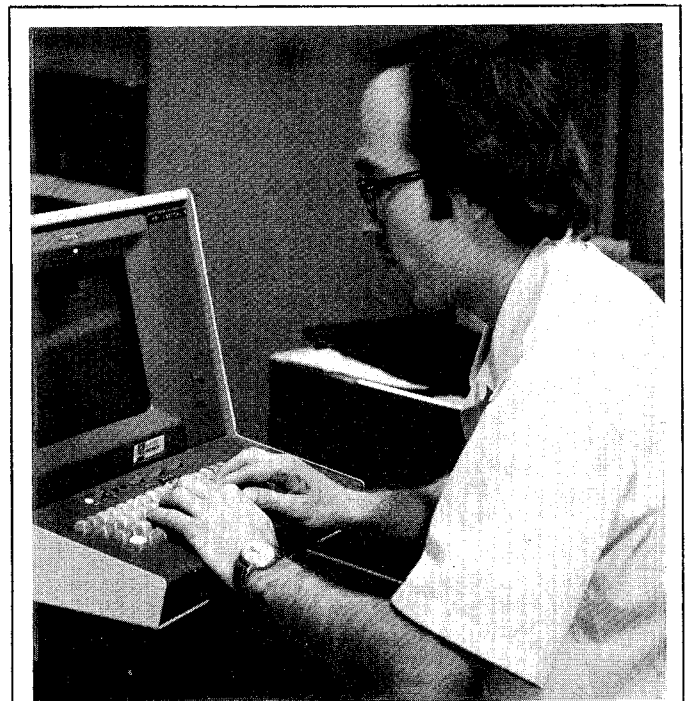
--Photo by Joe Faust

Visiting experimenter Gus Apai, from Lawrence Berkeley Laboratory, is shown at the teletype control for the ultra-high-vacuum, grazing-incidence monochromator, an instrument that was designed and built at Xerox Corporation and at the University of Wisconsin.

--Photo by Joe Faust

Ben Salsburg of SSRP is shown communicating with the SPEAR control room in order to adjust the position of the SSRP beam. Unlike charged-particle beams, which can be steered and focused magnetically, the synchrotron radiation beam emerges along a path that is tangential to the orbit of the circulating electrons in SPEAR. Thus the synchrotron radiation beam is steered by adjusting the orbit of the SPEAR electron beam. A simple and effective orbit-control circuit was designed by Ewan Paterson and was installed by the SPEAR operators working under Tom Taylor. This system has made it possible to position the synchrotron radiation beam with an accuracy of a fraction of a millimeter at a distance of 20 meters from SPEAR, thus eliminating the need for frequent realignment that is the norm at other synchrotron radiation labs.

Ben Salsburg is in charge of electrical systems at SSRP, working with experimenters to get their equipment set up and operating properly. He is presently designing a readout system for a multi-wire proportional chamber array that will be used in x-ray diffraction studies--an example of high-energy-physics technology adapted to other research uses.

D. THE SSRP EXPERIMENTS

Although SSRP has only been in operation since May 1974, it has already achieved experimental results that have attracted a good deal of attention. Six papers based on work done at SSRP were presented at the International Conference on Ultraviolet Radiation Physics held in Hamburg, Germany, in July. In addition, about 80 scientists from all parts of the U.S. and from Western Europe recently attented an SSRP Users Conference at SLAC to discuss the research possibilities at SSRP.

In the following paragraphs we first describe the mechanism by which experimental proposals are acted upon at SSRP, after which we go on to a description of some of the actual experiments that have already been carried out or are presently planned.

1. *Proposals And Decisions*

Like SLAC, SSRP is a national facility for basic research. This means that SSRP's facilities are available to any qualified user. Experiments presently under way at SSRP include scientists from the University of Washington, from Caltech, from Xerox Corporation, from Bell Telephone Labs, from the University of Illinois, from UC-Berkeley, and of course from Stanford. More than a dozen new proposals have been received from these and other institutions, including Argonne National Laboratory, Harvard University, and the National Bureau of Standards.

Proposals for experiments are sent to SSRP's Director, Professor Doniach, who seeks advice from several different sources before reaching his decision. The proposals are reviewed for scientific merit by SSRP's Program Review Panel, a group that is similar to SLAC's Program Advisory Committee. In addition, outside referees (not football) are called upon for advice in their particular fields of expert knowledge. And SSRP's staff provides advice about technical feasibility in much the same way that SLAC's Experimental Facilities Department advises the Director of SLAC. The only role which SLAC itself plays in this process is to exercise control in safety matters--particularly radiation safety--and to set vacuum standards for those experiments that will be connected to the line leading to the SPEAR vacuum system. Once a proposal has been accepted, it is scheduled into the overall SSRP program, and is eventually carried out with the assistance of the SSRP staff.

The construction of SSRP was funded by the National Science Foundation, starting in June 1973. Because of the fact that the SPEAR designers had had the foresight to fit the ring with a small tangential 'spout' which merely had to be uncapped (the open spout lets out less than .002 of SPEAR's total synchrotron radiation)

it was possible to begin some preliminary pilot
studies with the radiation as early as July 1973.
By May 1974 the facility was fully operational,
thanks in large measure to the outstanding co-
operation and assistance provided by SLAC (see
separate box on this page). Thus SSRP was able
to get in about 7 weeks of solid experimental
running before the scheduled shutdown of the
storage ring for conversion to SPEAR II. Dur-
ing this run there were three types of experi-
ments of considerable interest carried out at
SSRP, which we'll describe in the next three
sections of this article.

2. EXAFS: Extended X-Ray Absorption Fine Structure

The apparatus used in the EXAFS experiments
consists of a variable-energy monochromator that
directs x-rays with a well-defined energy
($\pm$ 1 electron volt at about 10 keV) onto a tar-
get material at intervals of about one pulse
second. Some of these x-rays knock loose inner-
shell electrons (those closest to the nucleus)
from the atoms in the material. That is, in the
right circumstances an electron will absorb the
energy of an incoming x-ray and recoil complete-
ly out of the atom. Ion chambers placed just
in front of and just behind the target material
are used to measure the x-ray flux that arrives
at, and is transmitted through, the target. A
computer calculates the ratio of these measure-
ments (which is the absorption), steps the mono-
chromator to a new energy setting, then makes a
new measurement. Several thousand measurements,
each of which lasts from 1 to 5 seconds, are
made in rapid succession, and the results are
plotted on-line as well as stored in the comput-
er memory for later analysis.

The absorption of x-rays by matter follows
the characteristic pattern shown in Fig. 8.
The absorption peaks at a certain critical en-
ergy (different for each element), then tails
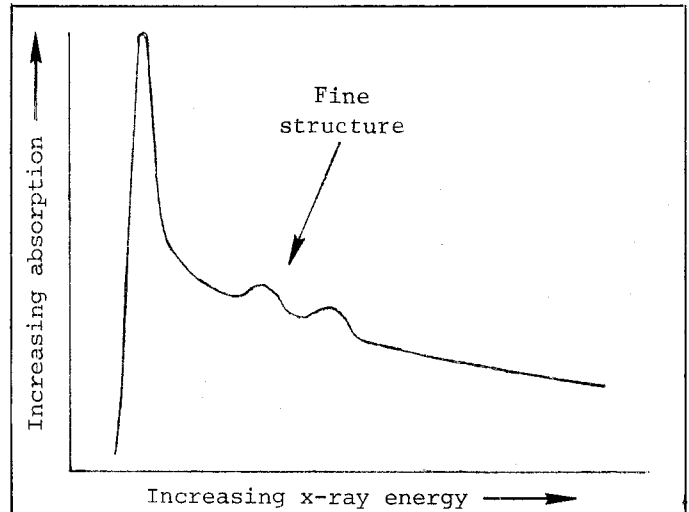off fairly slowly at still higher energies.

Fig. 8--Typical pattern of x-ray absorp-
tion by inner-shell atomic electrons. If the
emitted electron interacts with neighboring
atoms, the interactions will show up as fine
structure in the absorption curve.

To understand what happens to the freed
electron, we have to recall that electrons, like
other elementary particles, are not only little
bits of stuff but also that they can just as well
be thought of as waves. And when an outgoing
electron wave leaves its home atom it is quite
likely to get scattered (bounced around) by the
neighboring atoms. This scattering or inter-
action with the neighbors shows up in the ab-
sorption measurements as a series of small bumps
or wiggles (that is, as *fine structure*) in the
energy region just above the main absorption
peak. Therefore--and this is the point--any
change in the arrangement of the neighboring
atoms will *show up as a change in the fine
structure.*

Thus the EXAFS technique gives us a power-
ful tool for gaining detailed information about
the local environment of an x-ray absorbing atom.

This technique has been known for many years (it was first explained by Kronig in 1931), but there were practical problems connected with doing the experiments. When conventional x-ray tubes are used to produce the radiation, it is not uncommon for one complete energy scan of a single material to take a few *days*, or even *weeks,* to be completed. During such long running periods there are fluctuations in tube output and in detector sensitivity, with the result that the experiments were both painfully long and not very precise.

The high intensity and excellent collimation of SPEAR's synchrotron radiation makes it possible to measure a complete absorption spectrum with excellent accuracy in a typical period of about *25 minutes*, or roughly 1000 times faster than with earlier methods. An example of an EXAFS measurement done at SSRP is shown in Fig. 9. This experiment was a study of the copper-atom environment in the compound copper sulphate ($CuSO_4$). The first measurement was on the crystalline material itself, and the second after it had been dissolved in water. A completely different spectrum appeared for the second measurement, and it is now thought that the change resulted from a surrounding 'cage' of water molecules that had been established around the copper atom in solution. On a later measurement ammonia was added to the solution, and again the spectrum changed as a result of the formation of copper-ammonium ions. This experiment marks the first time that direct structural data of this kind has been possible in the field of solution chemistry.

One additional EXAFS application is worth

Copper
Porphyrin
(77° K)

Increasing absorption ——→

Increasing x-ray energy ——→

Fig. 9--EXAFS spectrum of tetraphenyl copper porphyrin at 77° K. The fine structure to the right of the peak indicates that the electron that was knocked out of the inner atomic shell of the copper atom is being interfered with by neighboring atoms.
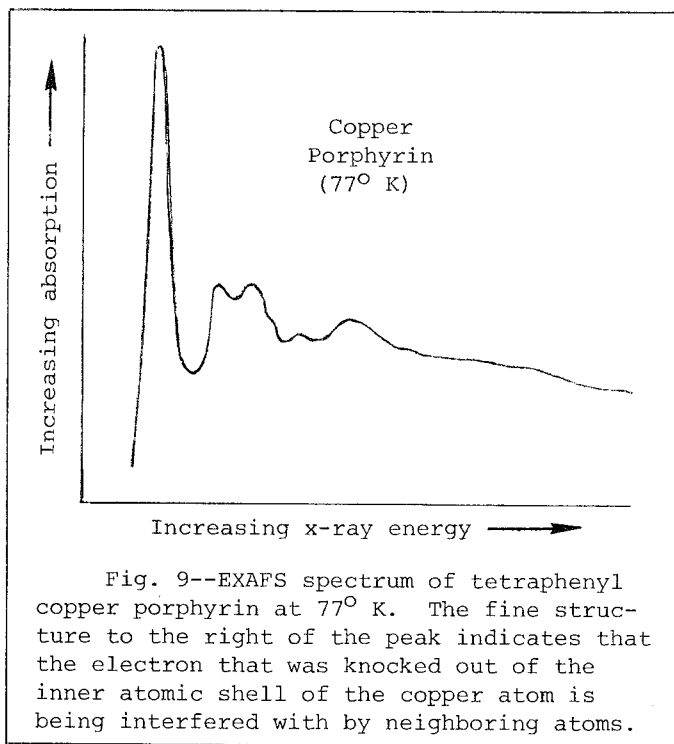
noting. There are certain biological processes, in particular enzyme mechanisms, which depend critically on the precise location of a specific atom in a complex biological molecule. Since EXAFS probes the surroundings of a particular x-ray absorbing atom, the technique can be used, for example, to measure the slight shift in position that the iron atom in a hemoglobin molecule makes when the hemoglobin (in red blood cells) picks up or releases the oxygen it carries.
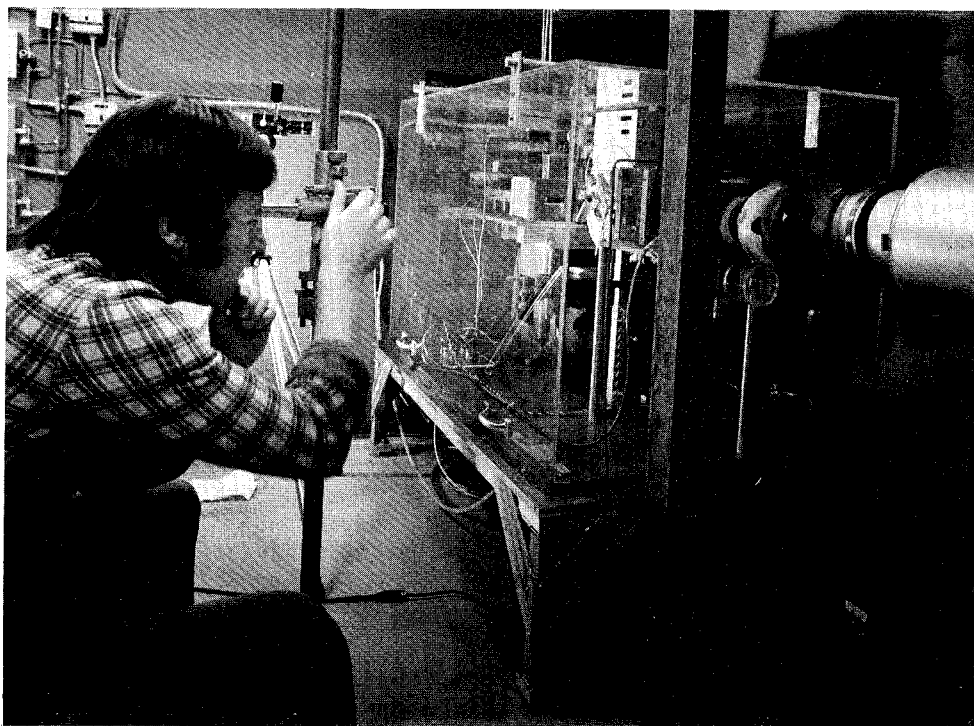
Visiting experimenter Pierre Lagarde, from the synchrotron radiation research center at Orsay, France, is shown aligning the crystal monochromator that is used in the EXAFS studies at SSRP.

--Photo by Joe Faust

3. Photo-Electron Emission

The process by which ultraviolet light or x-rays knocks an electron out of an atom is called the *photo-electric effect* (it was first explained by Einstein in 1905). By measuring the energies and angular distributions of the knocked-out electrons it is possible to learn a good deal about the electronic structure of the various elements. Some electrons in atoms are held tightly in an inner shell, while others wander more freely around the atom's outer periphery.

Three different experimental groups are presently pursuing studies of this kind at SSRP. Much of this work takes advantage of the fact that the synchrotron radiation from SPEAR has a unique time structure. Although the circumference of the SPEAR ring is about 800 feet, the machine is operated in the 'one-bunch mode,' which means that the single bunch of electrons circulating in the ring only takes up a space about 15 inches long (SPEAR II's new RF system reduces the bunch length to about 3 inches). Thus an observer standing in the SSRP facility and looking at SPEAR would see a flash of light that lasts for about 10^{-10} second, then darkness for about 10^{-6} second, and so on.
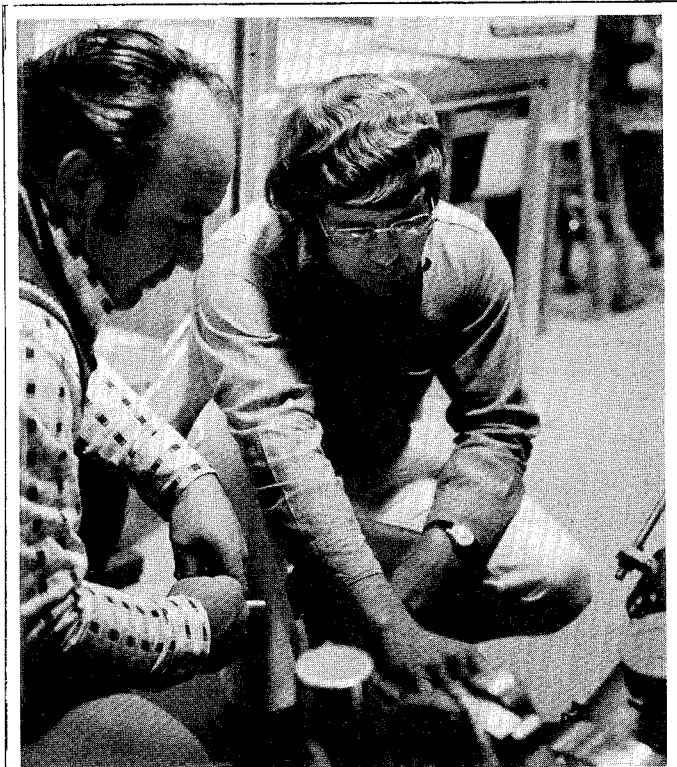

--Photo by Joe Faust

Vern Jones (left) and James Leland Stanford (yes, a direct descendant of the University's founder) are shown adjusting a mirror on the 8° beam line at SSRP. This beam line was built as a collaborative effort between SSRP and the U.S. Navy Michelson Lab at China Lake, California.

Experiments at SSRP take advantage of this comparatively long period of darkness between flashes to make time-of-flight measurements of the velocity of the knocked-out photo-electrons. This is done simply by measuring how long it takes the electron to travel from the target to the detecting apparatus. Knowing the velocity, the electron's energy and momentum can be calculated, and this information, together with the measured angular distribution patterns, is what is needed to infer the particular atomic structure from which the electron came.

Information about the way in which an atom's structure is determined by the particular configurations of its electrons is of paramount importance in trying to understand the properties of materials. SSRP's work in this field seems likely to be an important contributor to understanding the surface properties of metals, semiconductors and insulators, with applications to such practical areas as the fabrication of electronics components and the catalysis of chemical reactions.

$$\frac{\partial^2 \sigma}{\partial \tau \partial \psi^2}$$
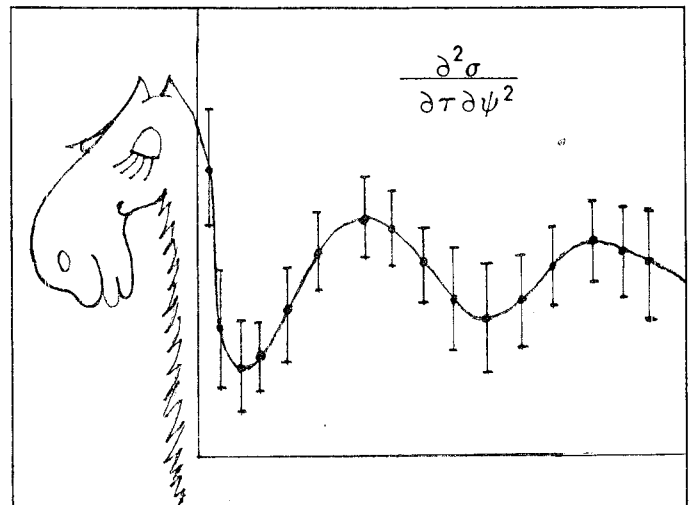
4. Biological X-Ray Diffraction

The apparatus for using monochromatized synchrotron radiation to study the structure, and changes in structure, of biological systems has been used for some preliminary experimental work to date. X-ray diffraction patterns have been obtained from frog's-leg muscle and also from rat-tail collagen. (SSRPers are now in the habit of opening packages rather slowly, after several one-pound-size bullfrogs jumped out of one box.) The earliest exposures took several minutes, but recent apparatus improvements, coupled with the expected higher intensity from SPEAR II, make it likely that exposure times of less than one second will be feasible. So short an exposure time opens up the exciting possibility of studying the rapid changes that occur in many biological systems--for example, muscle and retinal tissue. Toward this end, there is work now being done on possible electronic detection techniques (e.g., wire chambers) to replace the film that is commonly used.

E. SPEAR II AND BEYOND

As far as SSRP is concerned, SPEAR II is even more of a good thing. We've already mentioned the increase in synchrotron radiation intensity that is expected. The combination of higher energy and greater beam current in SPEAR II will result in synchrotron radiation energy losses of up to 150 kilowatts per beam. This compares with the previous value of about 12 kW from SPEAR I. This roughly 12-fold increase in power also applies to the radiation that comes out to SSRP through the little peephole in SPEAR.

The prospective research potential of SSRP has already produced a great deal of interest among potential experimenters throughout the U.S. As we noted earlier, the physical facilities at SSRP are now set up to handle as many as 5 simultaneous experiments. In response to the expected demand, it may be possible to squeeze in another 1 or 2 set-ups in the present space. In the longer run, however, the better solution would be to have a second main beam run from SPEAR into the new part of an expanded SSRP facility. Plans for such a possible expansion are now being worked on.

For the even longer term, there has been some thought given to the relationship, if any, between SSRP and the proposed PEP storage ring facility at SLAC. Even if PEP is authorized for Fiscal Year 1976, as proposed, it will not be on the air until 1979 or 1980, so there is enough time to consider SSRP's lot in life in the meantime. Speculatively, however, we could imagine a situation in which SPEAR would eventually be operated solely for SSRP's purposes, after the high-energy physics interest had swung over to PEP. Equally imaginable is a revamped SSRP facility that would move over to PEP to capitalize on the higher energy and intensity, and other factors.

But then SSRP still has to learn to walk before it starts to run, since we've done little more than scratch the surface of the present exciting research possibilities. Once we have a few years of experimentation under our belts, the future will doubtless seem clearer.

We'll sign off here with an invitation: if anyone at SLAC would like to take a look around the SSRP facility, we'd be happy to arrange something. Just give a little advance notice by phoning SLAC Ext. 2874.

--Herm Winick & Bill Kirk

MORE ABOUT EXAFS AND SSRP

In their first experiments at Stanford, the [SSRP] experimenters studied some simple systems to check out the characteristics of the new source. They studied atoms, simple molecules, pure crystalline materials and simple compounds and confirmed earlier measurements made with traditional sources. With the krypton atom they showed there was no marked x-ray structure. Next, with the Br_2 molecule they measured the phase shifts the electrons experienced when scattered from the surrounding atoms. Then $GeCl_4$ and $Ni(CO)_4$ were studied to investigate the possible effects of multiple scattering and shadowing. They also studied semiconductor systems such as CuBr and GaAs and Ge to investigate the effect of ionicity of the band on the EXAFS structure.

The experimenters then wanted to demonstrate some of the potentialities of the technique. To show possible biological applications, they studied nickel and copper porphyrin and hemoglobin. In the porphyrins the metal atom is present to only one part in 50 or 100; the group was able to show that a good spectrum was still obtainable under these conditions. In hemoglobin, the iron atom in the porphyrin ring represents only about one part in 10,000; even in such a small proportion the experimenters found significant EXAFS

structure. [They are] hopeful that the technique may be applied to oxygenation--by taking a spectrum of unoxygenated hemoglobin and then one for oxygenated hemoglobin one could learn how the immediate structure around the iron is affected by the presence of oxygen.

The technique has much potential in applications where the local environment around a given atom is of special interest, particularly for noncrystalline systems . . . . To demonstrate potential applications to chemistry, the experimenters compared spectra for bromine salts in solid form and in a water solution. The formation of hydrated bromine ions was demonstrated by the identity of bromine EXAFS structure for dilute solutions of different bromine salts . . . it should be possible to extract information on the structure of the hydrated ion by more detailed analysis of the spectra.

It might be possible to study a variety of chemical reactions . . . on a real-time basis by looking at reaction intermediates. To be feasible, one would like a factor of ten higher intensity (which will be available as a result of the upgrading program) for the x-ray source and measurement times in the 1-100 millisecond range.

--Physics Today, October 1974