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THE STANFORD SYNCHROTRON RADIATION PROJECT (SSRP)†

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Summary

The Stanford Synchrotron Radiation Project is a new national facility for UV and X-ray research using synchrotron radiation from the storage ring SPEAR. This ring now operates in colliding beam mode with E(stored beam energy) varying from 1.5 to 2.5 GeV and with 15 to 45 mA in each beam. Improvements in mid-1974 will raise the energy to $\gtrsim$ 4 GeV with expected currents of up to 100 mA in each beam. The critical energy of the synchrotron radiation spectrum varies as E^3 and is 11 keV for E = 4 GeV. Up to seven experiments can share a beam run which accepts 11.5 mrad of radiation. The UV and soft x-radiation are deflected at grazing incidence on ultra smooth platinum plated copper blocks and focused on custom built, high vacuum, high resolution monochromators. X-radiation above about 3.5 keV emerges from a 630μ thick beryllium window assembly. Sensors in the beam run detect high pressure or contamination and cause valves to close isolating the beam runs from each other and from the SPEAR vacuum system. Shielding and interlocks permit experimenters to adjust their equipment with beam shutters closed and to be within about 1 m of their equipment during operation with shutters open. A broad ranging program of research will be pursued including studies of UV and x-ray photo-electron spectroscopy, extended x-ray absorption edge fine structure, x-ray diffraction on biology systems, compton scattering, x-ray absorption x-ray induced luminescence, sub-nanosecond time constant measurements on solids, and UV reflectivity.

Introduction

SSRP utilizes synchrotron radiation from circulating electrons in the storage ring SPEAR. SSRP has been funded since June 1973 by the National Science Foundation and is administered by the W. W. Hansen Laboratories of Physics at Stanford University. SPEAR is a high energy electron-positron colliding beam storage ring located at the Stanford Linear Accelerator Center (SLAC), funded by the Atomic Energy Commission. Prospective users of SSRP should contact the Director, Professor S. Doniach or the Deputy Director, Professor W. Spicer, at the W. W. Hansen Laboratories of Physics.

SSRP is open to all qualified users. Experimental proposals are reviewed by the Director, advised by a Proposal Review Panel, outside referees, and the SSRP staff. Early submission of proposals is recommended. SLAC exercises control over radiation safety and also sets vacuum standards for experiments which will connect online to the SPEAR Vacuum System.

Characteristics of SPEAR

Some basic synchrotron radiation relationships are given in Table I. Additional synchrotron radiation relationships are given by Rowe[1] and Winick.[2] The storage ring SPEAR has been described in the literature.[3] The particular parameters of SPEAR that are relevant to synchrotron radiation are listed in Table II. The spectral distribution of the radiation is shown in Fig. 1. The data given in Table II and Fig. 1 are obtained using the result of Mack.[4] SPEAR has a bending radius of 12.7 m. The radiation is highly polarized with the E vector in the plane of the acceleration.

BASIC SYNCHROTRON RADIATION RELATIONSHIPS

ELECTRON ENERGY:	E (GeV)
RADIUS OF CURVATURE:	R (METERS)
ELECTRON CURRENT:	I (AMPERES)

$$\frac{\Delta E}{\text{TURN-ELECTRON}} = 88\,\frac{E^4}{R}\ (\text{keV});\ \epsilon_c = 2.2\,\frac{E^3}{R}\ (\text{keV})$$

$$\text{TOTAL RADIATED POWER} = 88\,\frac{E^4}{R} \times I\,(\text{kW})$$

$$\text{EMISSION ANGLE} \approx \frac{1}{\gamma} = \frac{mc^2}{E} = 2\times10^{-4} \text{ at } 2.5 \text{ GeV}$$

$$\frac{N_\gamma}{\text{TURN-ELECTRON}} \approx \frac{\Delta E/\text{TURN-ELECTRON}}{\epsilon_c} = 40\,E$$

TABLE I

SPEAR now operates for colliding beam experiments with one RF bunch per beam at energies up to 2.5 GeV per beam (limited by RF voltage). The current is limited by the maximum allowable incoherent tune shift ($\Delta\nu \approx .05$) due to beam-beam interaction. This limit increases with increasing energy. With the present SPEAR operational configuration, the currents corresponding to this limit are shown in Table II. Machine studies on SPEAR are in progress to increase the beam cross-section at the interaction point so that larger currents and larger interaction rates (luminosity) can be achieved, especially at the lower energies. Larger currents can of course be stored in a single beam (over 200 mA has been stored in one electron bunch and even more is possible if more of the 40 RF bunches are filled) but present plans call for synchrotron radiation operation only during colliding beam experimental runs. The water-cooling of the SPEAR vacuum chamber is adequate for synchrotron radiation losses of up to 150 kW per beam.

The beam decays with a lifetime that depends on

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energy and current. At 2.5 GeV the lifetime is 2 hours with 45 mA in each beam and increases to 4 hours with 30 mA per beam. Typically it takes 15 to 30 minutes to fill SPEAR with 2 beams, following which beams are stored and made to collide for several hours, after which the cycle is repeated.

PARAMETERS OF SPEAR

	UNTIL 7/74			AFTER 11/74			
ACCELERATING FREQ. (MHz)	51			358			
PULSE DURATION (10^{-10} sec) (FWHM)	8 to 16			1 to 2.4			
ORBITAL FREQ. (MHz)	1.28			1.28			
E_e (GeV)	1.5	2.0	2.5	3.0	3.5	4.0	4.5
I_e (mA)	20	25	45	50	75	75	45
RADIATION LOSS (kW)	0.70	2.8	12	28	78	135	130
ϵ_c (keV)	0.58	1.4	2.7	4.7	7.4	11	15.7

TRANSVERSE ELECTRON BEAM SIZE AND DIVERGENCE AT SYNCHROTRON RADIATION SOURCE POINT (TYPICAL AT 2.5 GeV)

	x (mm)	x'(mrad)	y (mm)	y'(mrad)
FWHM	3.22	0.566	1.59	0.266

TABLE II

During the summer of 1974 the magnet power supplies and the RF system will be modified to permit beam storage up to 4.2 GeV or more. The new RF system will produce 500 kW at 358 MHz. The present RF system produces 160 kW at 51 MHz. Higher colliding beam currents are possible at the higher energies reaching an expected peak of 100 mA at 3.8 GeV. Above 3.8 GeV the expected beam current falls off due to RF voltage limits. In addition to the dramatic improvement the higher currents and energy will make in synchrotron radiation power and critical energy, ϵ_c, as shown in Table II, the higher frequency will reduce the synchrotron radiation light pulse to $\sim 10^{-10}$ sec making possible experiments requiring fast time correlations.

Plan of the Synchrotron Radiation Facility

A prefabricated steel building 12 m wide, 24 m long and 7.3 m high has been constructed adjacent to SPEAR as shown in Fig. 2 and Fig. 3. The building is well insulated and temperature controlled and has a thick (30 cm) concrete floor for stability. Vibration sources (such as compressors) are located outside the building and decoupled from the building and floor.

About 11.5 mradians of synchrotron radiation, corresponding to 15 cm of curved path in a SPEAR bending magnet, emerges tangentially into a high vacuum pipe. This horizontal fan of radiation is split three ways by reflection at grazing incidence on two remotely movable ultra-smooth platinum-plated copper blocks[5] placed 6.5 m from the source point. One of these mirrors intercepts the outer 2 mrad of synchrotron radiation at a horizontal grazing angle of incidence of 2° resulting in a horizontally focused 4° deflected beam containing photons with energy up to about 2 keV. A plane mirror intercepts the inner 3 to 6 mrad at a vertical grazing angle of incidence of 4° causing the beam to rise at 8° from the median plane. This rising beam contains photons up to 300 eV. Since SPEAR can produce up to 25 W of synchrotron radiation per mrad these mirrors are cooled thermoelectrically.

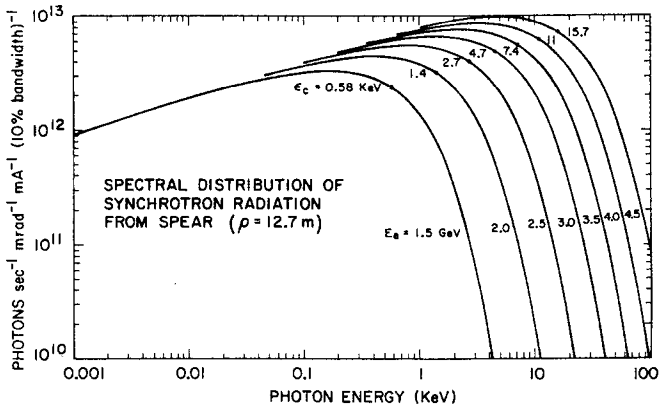
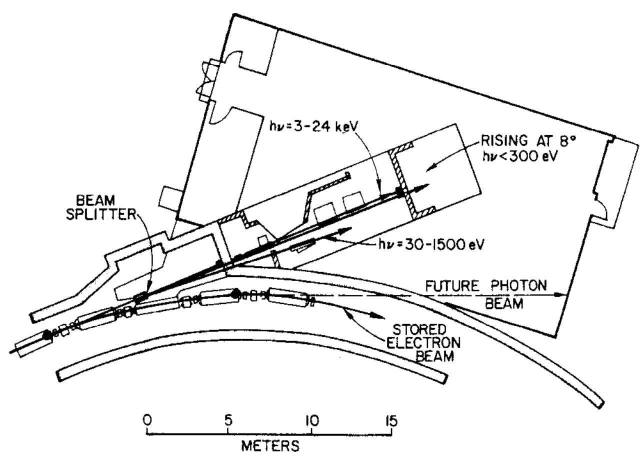


Figure 1

The central part of the beam contains 3 to 10 mrad of radiation which is not deflected by mirrors. This radiation proceeds down the high vacuum beam pipe, passes through a pair of water-cooled 65μ thick beryllium foils and exits from the vacuum system 10.5 m from the source point through a pair of 250μ beryllium windows. Significant transmission begins at about 3.2 keV. This window system has been used successfully over extended running periods with SPEAR operating at 2.4 GeV with currents up to 50 mA. In-vacuum water-cooled carbon foils[6] are being considered to handle the higher power densities that will be present when SPEAR operates at higher energy.

After emerging from the SPEAR vacuum system the x-rays travel in a helium atmosphere into a shielded area in which several crystal monochromators and experiments will be installed. Some of these direct the monochromatic radiation upwards to an upper level experimental area as shown in Fig. 3 and Fig. 4.



SSRP FACILITY LAYOUT

Figure 2

An elevated concrete slab 4.5 m wide, 12 m long, and 2.4 m above the floor serves as a second level for installing experimental apparatus. The rising 8° beam line vacuum pipe penetrates this slab as shown in Fig. 3. Electrical services, compressed air, helium and water services are installed at several locations along the perimeter of the slab. Vacuum controls, radiation protection controls, and signals to and from the SPEAR and SLAC control rooms are centralized in an adjacent control room.

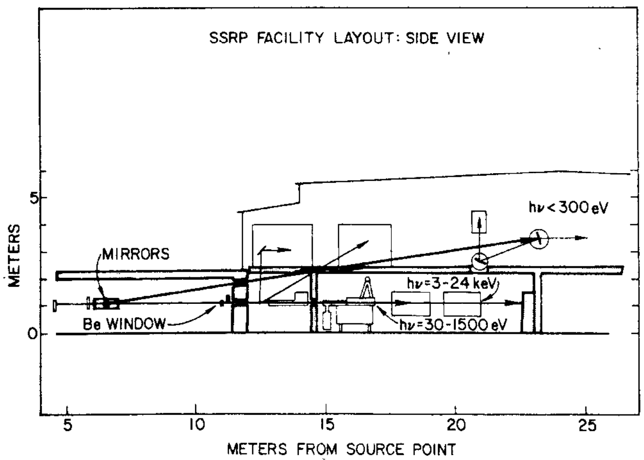


Figure 3

The synchrotron radiation beam can be independently steered so that it can be reproduced spatially, correcting for variations that may occur from run to run, or variations that may be required for positioning the two colliding beam interaction points. This is accomplished by powering steering coils some of which are arranged in pairs to produce local orbit distortions (beam bumps) in the vicinity of the synchrotron radiation source point.

Vacuum System

The vacuum system is built to SLAC specifications[7] and is all metal and bakable. The central beam pipe extends to 10.5 m from the source terminating at the beryllium window assembly within the SPEAR tunnel. The 4° and 8° beam runs continue in vacuum in the synchrotron radiation building and extend to 16 m and 23 m from the source point.

All metal ultra-high vacuum gate valves isolate the beam runs from each other and from the SPEAR vacuum system. Synchrotron radiation strikes only water-cooled surfaces and movable water-cooled absorbers may be remotely inserted to block the radiation.

Ionization gauges and fast sensors[8] are used to detect leaks and desorption diodes[9] sense contamination. These devices are monitored by a vacuum control system which causes valves to close automatically in the event of vacuum problems. Fast isolation from SPEAR is provided by a vane which closes in 30 msec.[10]

Radiation Protection System

A system of beam stoppers, a permanent magnet, radiation monitors and interlocked gates is installed to protect personnel from exposure to synchrotron radiation or the high energy radiation that could result in the worse case event that injected or stored beams are lost in SPEAR in certain critical locations. With appropriate beam stoppers closed, occupancy is safe in the immediate vicinity of experiments during all phases of SPEAR operation. With beam stoppers open experimenters are able to occupy areas within about 1 m of beam lines. Access to the SPEAR tunnel and to the primary x-ray beam line in the SSRP building is remotely controlled by SLAC operators. Access to small secondary beam areas is experimenter controlled.

Status of the Project

At this writing (April 1974) a pilot project beam run has been in operation since July, 1973, providing radiation to an x-ray photo-electron spectroscopy (XPS) experiment and an extended x-ray absorption fine structure (EXAFS) experiment. This equipment is now being removed and the full facility with all beam runs, control systems, personnel protection systems, shielding, etc., is being installed. Operation with five experiments is planned for May and June, 1974. Following this the SPEAR ring will be down for several months for the improvement program which will allow storage of beams with energy in excess of 4 GeV. Some synchrotron radiation should be available in the latter part of 1974 and routine operation for colliding beam and synchrotron radiation experiments is scheduled to commence in late 1974 or early 1975.

Experimental Program

X-ray Beam Line (hν > 3 keV)

Several different groups will set up spectrometers using the x-rays available in the main beam line. The activities in this beam line include:

X-ray Photo-Electron Spectroscopy (XPS). A 3-crystal monochromator designed to produce intense radiation at 8.0 keV with a bandwidth of 0.1 eV has been built by P. Pianetta of Stanford and has been operated in a double crystal configuration. A high vacuum sample chamber and electron energy analyzer built by I. Lindau of Stanford is also complete. The equipment was used in a pilot project x-ray beam and has produced its first data on the 4f levels of metallic gold.[11] A broad-ranging program of research in the fields of solid state, materials science, inorganic and organic chemistry will be led by W. Spicer, I. Lindau and S. Doniach of Stanford.

Extended X-ray Absorption Fine Structure (EXAFS). Initially one EXAFS channel-cut single crystal x-ray spectrometer with associated detectors and data processing equipment is being assembled. Several investigators (including A. Bienenstock, S. Doniach, S. Hunter, B. Kincaid, and M. Weissbluth of Stanford, D. Sayers and E. Stern of the University of Washington, F. Lytle of the Boeing Aerospace Company and P. Eisenberger of the Bell Telephone Research Laboratories) will use EXAFS studies to determine the radial structure functions associated with specific elemental constituents in a variety of complex materials including gases, liquids, glasses and certain complex crystalline materials in which the environment of one particular kind of atom is important; e.g., the iron atom in hemoglobin.

X-ray Diffraction. A group from the California Institute of Technology (J. Baldeschweiler, R. Stroud, and N. Webb) are building a focusing monochromator with low angle diffraction camera for x-ray diffraction studies of biological systems including time dependent diffraction. Samples to be studied include proteins, enzymes, muscle, and membrane systems.

A group consisting of K. Hodgson and E. Shooter of Stanford and L. Jensen of the University of Washington, Seattle, are proposing to install a diffractometer at the focus of the monochromator to do structural studies on protein single crystals.

Compton Scattering. P. Eisenberger of the Bell Telephone Research Laboratories is planning to build a triple axis monochromator - energy analyzer system to measure x-ray inelastic scattering. This is planned for use in SPEAR II (early 1975). Among other measurements that of the Compton profile in solids and molecular systems gives very detailed information about electronic charge distributions which can be used to test specific theories of chemical bonding.

4° Beam Line ($25 < h\nu < 2500$ eV). A flexible facility, entered around a specially designed grazing incidence monochromator with a fixed exit slit, will be set up in this beam line under the direction of F. C. Brown, R. Bachrach, and S. Hagstrom of the Xerox Research Center at Palo Alto and Stanford University. A beam splitting mirror will provide about 2 mrad to this line, focused in the horizontal direction. Research on this beam line will include studies on high resolution soft x-ray absorption spectroscopy, x-ray induced luminescence, photo-emission spectroscopy by time of flight measurement and subnanosecond time constant measurements on solids.

8° Rising Beam Line ($h\nu < 300$ eV). A specially adapted ultra-high vacuum normal incidence monochromator for this energy range is now being built by the McPherson Company under subcontract from China Lake for installation in the beam run. A group from the Michelson Laboratory at China Lake, led by V. Rehn (others include A. Bair, T. Donovan, D. Kyser, and J. Stanford), in collaboration with a Stanford group, will make reflectivity and photo-emission measurements. Differential reflectivity (electro- and piezo-reflectance) measurements are being planned.

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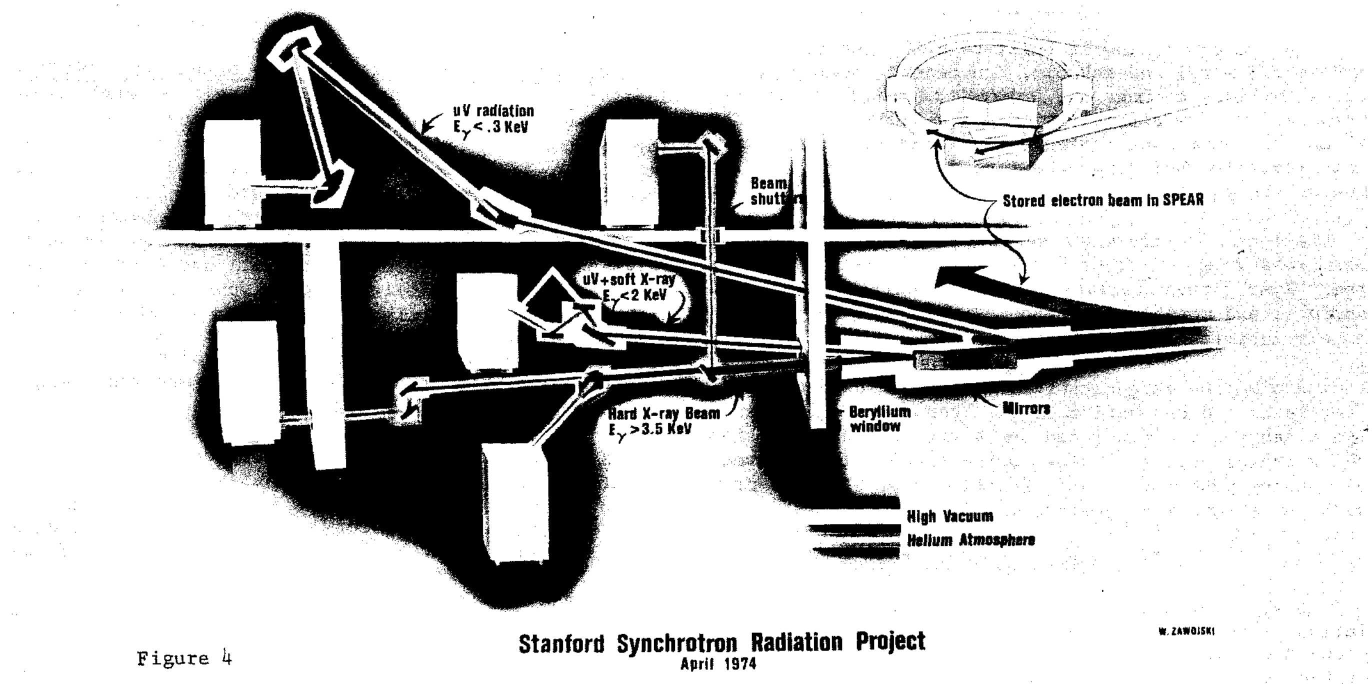

Figure 4