Center for X-Ray Optics

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Introduction

The Center for X-Ray Optics has made substantial progress during the past year on the development of very high resolution x-ray technologies, the generation of coherent radiation at x-ray wavelengths, and, based on these new developments, had embarked on several scientific investigations that would not otherwise have been possible. Our interactions with scientists outside Berkeley, in large part through our affiliates program, has led to our participation in a number of projects at other institutions. Our student program has been augmented by a new course, Introduction to X-Ray Physics, in the U.C. Berkeley Physics Department, and we were selected for a major University Research Initiative grant to establish this as a Center of Excellence for student research and training.

In the area of x-ray source development, major accomplishments included an understanding of the emergence of coherence from noise in high gain free electron lasers, the comparative performance of x-ray lasers and undulators as sources of coherent x rays, and the relative merits of compact synchrotrons and laser produced plasmas as sources of x rays for lithography and other laboratory experiments.

A major accomplishment in advanced instrumentation was the fabrication and testing of soft x-ray focusing lenses—gold Fresnel zone plates—with outer zone widths of 700 Å, able to focus soft x rays to 1000-Å spatial resolution with approximately 5% diffraction efficiency. These lenses form the basis for our biological x-ray microscopy efforts in collaboration with our colleagues at SUNY Stony Brook and at Brookhaven National Laboratory. The zone plate lenses were made in collaboration with the Nanolithography Group at IBM's Watson Research Center. Based on this new capability, biological studies of protein transport within secretory cells has just begun. U.C. San Francisco plays a major role in these experiments.

It is more difficult to focus hard x rays ($\lambda \sim 1$ Å). Here we have made substantial progress through the use of multilayer coatings on curved substrates. These reflective optics work at larger than usual glancing angles, set by the Bragg condition for the x-ray wavelength λ and the multilayer d spacing. As a consequence coated optics have several advantages over noncoated microscopes and telescopes: they are wavelength selective, they have a larger collection of solid angle, and, most importantly, classical aberrations are greatly reduced, permitting

improved image resolution and microprobe focusing. Systems were fielded in 1986 with both small laboratory tubes and synchrotron radiation sources. Submicron resolution was achieved with an 8-keV copper anode tube in our laboratory. Using synchrotron radiation from Brookhaven's x-ray ring, a 10- μ m diameter microprobe was formed with 10^8 photons/sec at 10 keV, in a 10% bandwidth. This unprecedented capability was then used to form elemental maps for the study material properties, inclusion in ceramics, biological structure concentrations, etc. In 1987 we anticipate this resolution toward a 1- μ m diameter microprobe at 10 keV with comparable flux.

Another major development involves a new class of high resolution monochromators and spectrometers for the soft x-ray region. These will have a major impact on spectroscopic applications of synchrotron radiation, line width measurements of x-ray lasers and thereby the time-dependent physics of lasing processes, studies of nonlinear absorption and transport in hot dense plasmas, as well as improved coherence length for x-ray microscopy and holography studies. Although the exact configuration depends on the application, the new class of instruments basically utilizes separated function optical components for two-dimensional focusing and dispersion, as well as the use of easily polished substrates such as spheres and flats. In some cases, particularly where resolutions ($\lambda/\Delta\lambda$) in excess of 10,000 are required, varied line space gratings are also employed. A variety of such projects are underway, one already in use, others to be fielded in 1987.

Other technical areas of note during 1986 included the first x-ray images of solar active regions using a normal incidence x-ray telescope, new x-ray photocathodes of very high detection efficiency based on solid Xe and Ar *condensed films* in which secondary electron mean free paths can be very long, and use of picosecond x-ray spectrometry to measure mass ablation rates from laser-irradiated fusion capsules.

Our synchrotron radiation projects group made substantial progress on the design and testing of beamlines and of beamline components that must function under high x-ray thermal flux conditions that are sufficiently high to melt mirrors and crystals without special measures. A water-cooled copper mirror that can absorb several kilowatts of power without excess distortion has been delivered to Brookhaven (NSLS) for use with the new soft x-ray undulator. A second system is to be installed on the VUV branch of the LBL/Exxon wiggler at Stanford (SSRL). Studies of thermally loaded mirrors and crystals, including finite element computational modeling and measurements of actual temperature contours, have been conducted at both Stanford (SSRL) and Cornell (CHESS). A high resolution spherical grating monochromator has been designed for initial use on the SSRL/VUV branch line, and for possible use on future high-brightness high-flux beamline facilities. The engineering group has also had a major involvement in the design and fabrication of state of the art periodic magnet structures, including a new 15-period wiggler for Beamline X at Stanford, the Livermore/University of California beamline.

Finally, there has been significant progress in the design of ever improved undulators and wigglers for uses involving both synchrotron radiation and free electron lasers. Generally, these new techniques combine permanent magnet materials and electromagnet techniques to control saturation effects, compensate for field errors, and generally lead to structure of greater field strength and closer-to-ideal field distributions on and off axis.

X-Ray Sources

Our broad interest in sources of x rays is reflected in recent comparative studies of x-ray lasers, plasmas, and undulators and in studies of compact synchrotron radiation sources and laser-produced plasmas—both possible sources of x rays for integrated-circuit lithography. The main thrust of our effort, however, remains the design and theoretical understanding of periodic magnetic structures—wigglers and undulators or, collectively, insertion devices—as sources of radiation. During the past year, our theoretical effort was directed toward unraveling the mechanism by which coherence emerges from “noise” in single-pass free-electron lasers. At the same time, we continued to refine our designs of insertion devices, putting forward candidate designs for the Advanced Light Source (ALS), and developing innovative approaches to incorporating permanent-magnet material into electromagnetic undulators and wigglers.

Partially Coherent Radiation from Undulators and X-Ray Lasers

Our earlier analysis of partially coherent x-rays generated through the use of undulators on high brightness storage rings has been extended to include the radiation from x-ray lasers, which have similar properties of partial coherence. We have also included line and continuum radiation from x-ray emitting laser produced plasmas.

Comparisons of the various radiation sources depends significantly on the intended application, and thus we find it necessary in some cases to compare peak or average coherent power, for various coherence lengths, or to compare peak or average spectral brightness for different relative bandwidths. The resulting curves have been widely distributed in the synchrotron, x-ray laser, and plasma communities. Two sets of curves are illustrated here in Figs. 1(a) and 1(b), separately comparing average coherent power and peak coherent power for selected coherence lengths. Note that the undulators dominate in the x-ray region near 10 Å, for both peak and average coherent power, but that the lasers dominate for peak power output at wavelengths longer than 100 Å. Tunability, polarization control, and megahertz repetition rates are additional advantages of the undulator systems.

Undulators and Wigglers for the Advanced Light Source

We have designed an initial selection of four undulators and one wiggler to be used in the Advanced Light Source, the low emittance (small phase space) electron storage ring to be constructed at Lawrence Berkeley Laboratory. Undulators are central to the photon capabilities anticipated for the ALS, which is optimized for the VUV and soft x-ray spectral regions. Wigglers will produce a copious flux of photons to energies up to 10 keV.

The tuning of undulator radiation in the fundamental is broad, but can be extended further. The use of third-harmonic radiation extends the spectral coverage significantly. Harmonics of fifth and higher orders are also present, but their spectral extension is less effective. In addition they are more sensitive to magnetic field errors. Thus we take the view that the first and third harmonics provide useful output.

The spectral flux and the spectral brightness of the selected insertion devices are shown in Figs. 2 and 3 respectively. The electron beam parameters are taken to be as follows: energy = 1.5 GeV, average current = 400 mA, horizontal emittance = 4×10^{-9} $\mu\text{m-rad}$, and vertical emittance = 4×10^{-10} $\mu\text{m-rad}$. We see that the undulators cover the VUV and the soft x-ray spectral region in an orderly and overlapping fashion.

Fig. 1. Average and peak coherent power for various sources of x rays, including undulators and plasma driven x-ray lasers. Coherent radiation is defined as being diffraction-limited transversely, with a longitudinal coherence length of one micron or longer.

Fig. 2. Spectral brightness as a function of energy for four possible undulators, one wiggler, and the bending magnets of the Advanced Light Source. For the undulators, the tuning range is shown for both the fundamental (solid lines) and the third harmonic (dashed lines).

Fig. 3. Photon flux curves are convenient for conceptualizing and planning new experiments. The curves shown above are typical of what can be expected with beamline efficiencies that vary from one experiment to the next. For wigglers and bending magnets, a 5-mrad horizontal collection angle is assumed. For undulators, solid lines are the fundamental, dashed lines are the third harmonic radiation.

Fig. 4. Average coherent power as a function of energy for five possible ALS undulators. Coherent power is defined as having full transverse coherence in a 1- μ m longitudinal coherent length.

Particularly interesting are the coherence properties of radiation for the ALS undulators. Coherence properties are related to focusability and the ability to form interference fringes. The coherent power of the ALS undulators, defined here as that portion of the radiation that is diffraction-limited and has a coherence length of 1 μ m, is shown in Fig 4.

High-Gain Free-Electron Lasers

Electrons passing through a simple undulator are initially uncorrelated, and they remain uncorrelated as they continue along the device. As the number of the undulator periods, N , increases, however, the interaction between the undulator radiation and the electron beam can lead to density modulations—"bunching"—in the electron beam and to an exponential amplification of the radiation. The undulator thus becomes a so-called high-gain free-electron laser (FEL), and the radiation emitted is called self-amplified spontaneous emission (SASE) by analogy to laser terminology. The transition from simple undulator to high-gain FEL is illustrated schematically in Fig. 5.

Since high-gain FELs operating in the SASE regime do not require the use of high-reflectivity mirrors to form optical cavities, they are promising alternatives to FEL oscillators as generators of intense, coherent radiation at wavelengths shorter than 1000 angstroms. At microwave wavelengths, the principle of SASE has been experimentally confirmed at the Lawrence Livermore National Laboratory.

Recently, we have made substantial progress in understanding how SASE emerges and propagates in long undulators. Our analysis, based on the Maxwell-Klimontovich equation, differs from earlier work in two respects. First, we use a microscopic description of electrons in terms of the Klimontovich particle distribution function. Second, the analysis is three-dimensional so that important issues such as guiding and transverse coherence can be clarified. Finding an explicit expression for the amplitude of the coherent amplification in terms of the input amplitude was a hitherto unsolved problem in three dimensions.

An important parameter characterizing high-gain FELs is the dimensionless parameter ρ , which is typically of order 10^{-3} . Figure 5 summarizes the evolution of simple undulator radiation to SASE. For $N \ll 1$, the radiation is an incoherent superposition of radiation from individual

Fig. 5. Schematic illustration of the evolution from an undulator to a high-gain free-electron laser. The appearance of electron "microbunching" is accompanied by an exponential gain in the intensity of emitted radiation. Saturation follows when electron motion ceases to remain in phase with the wavelength of the emitted light.

electrons, and it is only partially coherent transversely, owing to finite electron beam emittances. The bandwidth is about $1/N$. For larger N but with $0.1 < pN < 1$, the FEL interaction produces bunching of the electrons, resulting in enhanced radiation intensity and coherence. Typically, the radiation is dominated by a single transverse mode, which grows exponentially with length. The relative bandwidth is smaller than that of undulator radiation by a factor of $(pN)^{1/2}$. As seen in Fig. 5, exponential growth saturates when $pN \sim 1$. This occurs because of the increased momentum spread induced by the FEL action.

Sources for X-Ray Lithography

Synchrotron radiation facilities are well established as suitable sources for x-ray lithography. Of interest are more compact versions, perhaps less costly, that would be more suitable to a manufacturing environment. Also of interest is the possible use of x rays emanating from hot-dense laser-generated plasmas. Laser plasmas are well established for the efficient (20-80%) production of a quasi-continuum of sub-kilovolt radiation, and the fairly efficient (order 0.1%) production of individual (bound-bound) lines of photon energy in excess of 1 keV. The achievement of these high laser light to x-ray conversion efficiencies requires intensities of order 10^{14} W/cm² at 0.25 to 1 μ m laser wavelengths on appropriate target materials, and high peak powers of order 10^{10} watts for reasonable pulse duration and spot size. These plasmas produce exceedingly high photon flux levels in these very short temporal bursts (0.1 to 1 nsec), but a very low repetition rate.

To compete with synchrotron radiation facilities as compact x-ray lithography sources, the laser-plasma x-ray sources must now be extended to higher repetition rates, perhaps of order 1 kHz, combining previous high peak laser power, with new capabilities for high average laser power, of order 10^3 watts. Leading candidates for such an advanced compact source are KrF and Nd lasers. Substantial advances are needed for both classes of laser systems to advance to a competitive average photon flux level at the kilovolt photon energies required for microcircuit (chip) lithography. The solid state systems (Nd) require the development of a new host material, capable of maintaining low nonlinear refractive index properties for high peak power performance, while advancing substantially in pump efficiency and heat removal for high average power performance. The excimer gas lasers (KrF) must advance a factor of order 100 in peak power, through the use of sub-nanosecond pulse techniques, and another factor of order 10-100 in repetition rate and average power.

Assuming that one of these laser systems is developed in the next few years, we show in Fig. 6 how the synchrotron and laser systems would compare on the basis of x-ray photons per second (photon flux), within a 1% bandwidth $\eta\Delta\Omega \approx 2 \times 10^{-3}$.

For the laser plasma x-ray sources we assume 40% energy conversion to a 140-eV black body continuum, and a 1% conversion to a single x-ray line of highly stripped ions within the plasma. For peak photon flux the lasers gain an advantage of order 10^4 at 1 keV.

Fig. 6. Plot of delivered average photon flux as a function of photon energy for a compact synchrotron radiation source and a moderate-sized laser-plasma facility, assuming significant advances in laser technology. The computation assumes a peak power of 10^{10} W and a 1-kHz repetition rate for the laser.

X rays pose unique problems for optics designers because they cannot be focused by conventional means: Images cannot be formed by refraction, and specular reflectivity at near-normal angles is negligible. Fortunately, several other techniques are available for use at short wavelengths. Fresnel zone plates, for example, are circular structures whose alternating opaque and transparent zones serve to focus soft x rays by diffraction. And mirrors can be used effectively to focus higher-energy x rays by glancing-angle reflection. In addition, by using multilayers of atomic thicknesses, the usefulness of reflective optics can be substantially extended in several ways. During the past year, we made significant strides in developing each of these techniques, and we are successfully extending their practical application in experimental science. Other experiments in x ray imaging have included holographic studies and preliminary work with a new contact-microscopy station.

X-Ray Imaging and Applications

Zone Plates and Soft X-Ray Microscopy

Circular diffractive structures known as Fresnel zone plate lenses are one means of circumventing the difficulty of focusing soft x rays with wavelengths in the 10- to 100-angstrom region. When used with a suitable source of x rays, a zone plate can focus radiation to a resolution roughly equal to the outer zone width (see Fig. 7). In collaboration with colleagues at IBM's Watson Research Center, we have been fabricating gold zone plates of ever-improving quality and resolution. Fig. 8 shows a 57-mm-diameter zone plate with an outer zone width of 700 angstroms.

Fig. 7. Schematic diagram of Fresnel zone plate lens for diffractive focusing of x rays. Note that the outer line width (Δr) sets the spatial resolution of the microscope lens.

Fig. 8. Views of a gold Fresnel zone plate. The opaque outer zones are spaced 700 angstroms apart. Zone plates such as this have been used in an undulator based soft x-ray microscope at Brookhaven's NSLS to achieve a resolution approximately equal to the zone spacing. [Zone plates are fabricated in collaboration with IBM/Yorktown Heights.]

Fig. 9(a). One of our first views of an unaltered subcellular 1- μ m pancreatic granule, resolved to 0.1 μ m using a zone plate microscope and undulator radiation at 32 Å. Sample is in aqueous environment without fixation, staining, or sectioning. Because the aqueous environment was inadequately maintained in this dryer vesicle, the protein concentration, indicated by the blue regions, appears to be concentrated near in the center. The red areas indicate less x-ray absorption and thus lower protein concentration. The black area reveals minimal x-ray absorption in the surrounding water. [In collaboration with UC San Francisco, SUNY Stony Brook, IBM, and NSLS Brookhaven]

Fig. 9(b). High resolution soft x-ray image of a subcellular vesicle that transports digestive enzymes of the pancreas. Resolved to better than 0.1 microns, this is the first view ever obtained, by any method, of an unaltered subcellular component. The approximately 1- μ m diameter pancreatic granule was imaged in an aqueous environment without recourse to sectioning, staining, or fixation. Blue indicates the areas of greatest x-ray absorption and correlates with areas of high protein concentration. Red and black areas indicate less absorption and thus lower protein concentration. The fact that the blue areas (high protein concentration) are more prevalent away from the granule's center suggests that protein concentration is highest near the surface (membrane) of the wet vesicle. [In collaboration with UC San Francisco, SUNY Stony Brook, IBM, and NSLS Brookhaven]

The lens has 156 working zones and a 1.3-mm focal length at 31 angstroms. The 1300-angstrom-thick zones rest on a 1000-angstrom-thick silicon nitride substrate. A similar lens, with a 1000-angstrom outer zone width had a measured diffraction efficiency of 5.2%. The zone plate of Fig. 8 is expected to perform as well, with even better resolution. A 500-angstrom zone plate is nearing completion, and preliminary work has begun on 300-angstrom lenses.

The promise of these devices is to allow us, for the first time, to obtain images of intact living biological cells, as well as to probe inorganic materials with elemental specificity. Soft x-ray microscopes based on zone plates will be used, for example, to form subcellular images, resolved to better than 1000 angstroms and highlighting the concentrations of specific elements. The same microscope could also be used to study surfaces, thin-film formation, and material properties, with like capabilities. As an example of a biological application, consider one potential use. Models of enzyme secretion and vesicular transport in cells are widely accepted but only weakly and indirectly supported by experimental evidence. This is largely because it is not possible to follow such processes with the electron microscope in real time, and the objects in question (the vesicles) cannot, for the most part, be resolved by light microscopy. Our initial attempts to develop the means to carry out x-ray microscopy experiments involve the use of the scanning x-ray microscope at Brookhaven's National Synchrotron Light Source (NSLS), equipped with a zone plate of the kind just described, to image secretory cells from the pancreas of a rat. About 90% of the nitrogen in cells is contained within various proteins; as a result, measurements at the nitrogen *K* edge may provide us with the first direct estimation of the distribution of protein within various subcellular compartments of intact cells. Our first experiments along these lines, in collaboration with UC San Francisco, SUNY Stony Brook, IBM, and NSLS, produced preliminary results in early 1987 (Fig. 9). These new results included the first view of an unaltered subcellular component in its natural aqueous environment. The image, which was resolved to better than 1000 Å, did not require sectioning or the use of stain or fixation.

Hard X-Ray Microprobe

At higher photon energies zone plates become progressively more transparent, and thus less effective. Fortunately, in the hard x-ray region mirrors can be used to focus x radiation. We have constructed several instruments using multilayer-coated optical surfaces for imaging in x rays, including a laboratory x-ray microscope operating at 8 keV and an x-ray microprobe for use with synchrotron radiation. The latter instrument has been used at both NSLS and SSRL with encouraging re-

Fig. 10. A schematic of the geometry for the x-ray microprobe using synchrotron radiation.

sults. At both facilities it is possible to focus the radiation down to a spot of approximately $10 \times 10 \mu\text{m}$. This result is achieved through the use of a pair of mirrors in a Kirkpatrick-Baez geometry (Fig. 10), a configuration that eliminates the severe astigmatic aberration associated with a single glancing incidence reflector. At Brookhaven, the instrument operates in white radiation and the multilayer mirrors, acting in a manner analogous to Bragg crystals, select a slice of the spectrum about 1 keV wide at 10 keV. Focused on a sample, these x rays produce fluorescent x rays characteristic of the elements contained in it, which are analyzed by a solid-state detector to reveal the composition and elemental concentration of the sample. The instrument has high sensitivity to elements ranging up to zinc. Figure 11 is the spectrum of the fluorescent radiation from a $10 \times 10 \mu\text{m}$ area of an NBS spectroscopic (wheat flour) standard showing the detection of elemental masses of the order of 200 femtograms. Figure 12 shows the spatial resolution capabilities of the instrument; a scan along a blue-green algae filament reveals variations in the iron concentrations at the ppb level as the filament is scanned. Finally, Fig. 13 shows a scan of a fluid inclusion embedded in a simulated geological

Fig. 11. The x-ray microprobe can also be used to measure trace element profiles along a sample with high sensitivity. This figure shows the variation of iron concentration along a photo-active blue-green algae filament. In biological samples elemental concentrations of parts per million and femtogram sensitivity can be easily measured. [In collaboration with SSRL.]

Fig. 12. Concentrations of elements in an NBS wheat flour standard sample showing sub-picogram sensitivity. [In collaboration with NSLS and University of Chicago.]

Fig. 13. Two-dimensional distribution of calcium in a fluid inclusion imbedded in a simulated geophysical quartz sample. [in collaboration with Carnegie Institute of Washington]

Fig. 14. The x-ray microprobe is used to study the microscopic structure of material. These two pictures show the results of scans on a pair of ZnO ceramic samples. The scale bar represents 25 μm . (Left) SiC particles with diameters smaller than 20 μm dispersed throughout the sample volume. Black represents greatest concentration of SiC. (Right) Cracks and voids within another sample. Blue represents greatest concentration of ZnO; yellow to black are decreasing concentrations. The study of the creation and propagation of these microscopic imperfections is important to the understanding of the mechanical properties of advanced ceramic materials.

(quartz) sample. The scan clearly maps the calcium content of the inclusion, which has dimensions of the order of a few tens of microns. Since the inclusion is microns below the surface, it is inaccessible for analysis by other methods. Thus the x-ray microprobe promises to provide a new analytical method that will yield insight into important geophysical processes.

Solar Physics

Another of our multilayer optical instruments was recently used with a source of a very different sort. During the past year, we successfully collaborated with the Lockheed Palo Alto Research Laboratories to obtain an x-ray photograph of a solar active region, using for the first

time a normal-incidence x-ray telescope. The instrument was flown as part of a comprehensive rocket payload to study the sun's soft x-ray and extreme ultraviolet emissions. The telescope's passband covered two emission lines of Si 11^+ at 44.02 and 44.16 angstroms. Since ionization

Fig. 15. An x-ray photograph of a solar active region taken with a rocket-borne normal-incidence telescope developed in collaboration with the Lockheed Palo Alto Research Laboratories. Black represents no x-ray emission; red to yellow represents increasing amounts of x-ray emission.

of silicon to Si 11^+ requires temperatures of the order of 2.0×10^6 K, the photographs we obtained (see Fig. 15) show only the hottest part of the solar corona. Images such as these promise to yield a wealth of information on the structure and dynamics of the upper solar atmosphere, and we expect to continue this program using sounding rockets and, eventually, the space shuttle.

Holographic Microscopy

In earlier years, we have been successful in demonstrating that holographic methods, as used in the visible region, could be applied in the soft x-ray region. We showed that a hologram of a sparse, two-dimensional test object could be recorded on photographic film using 31-angstrom x rays and reconstructed using a helium-cadmium visible-light laser to give a final image resolution of about 1 μ m. During 1986 we sought to take the important and difficult step into the regime of spatial resolutions below 1000 angstroms. Our approach was to coherently illuminate the sample and a stack of resist detectors, as shown in Fig. 16. The first detector records a contact micrograph of the sample, and the three subsequent ones record a superposition of the partially attenuated incident beam and the diffracted beam from the sample; in other words, we get three holograms. Our eventual intention is to digitize and computer-process these redundant recordings to give values for the amplitude and phase of the diffracted field over the whole area of the recording. These data, plus similar data from different illumination directions, should allow a numerical reconstruction of the three-dimensional object.

Our earlier recordings were made using bending magnet radiation from the 750-MeV storage ring at NSLS, which required exposure times of about one day. However, late in 1986, we made about 25 multiple holograms of pancreatic cells, using the 10-pole undulator beamline (X-17) on the 2.5-GeV ring at NSLS. Exposures with the new undulator

Fig. 16. Experimental arrangement for recording a contact micrograph and three holograms at distances of 400, 800, and 1200 μ m from the sample. This setup was designed to allow three-dimensional reconstruction with better than 1000-angstrom transverse resolution.

radiation typically required about one hour and showed considerable improvement in quality. A further experiment in early 1987 generated another 75 holograms

The best recordings are of zymogen granules about 1 μm in diameter, which are enzyme-carrying vesicles of rat pancreatic cells. The holograms are recorded on copolymer resist layers deposited about 2000 Å thick on a thin (1200-Å) silicon nitride substrate and placed 200 μm downstream of the sample. The hologram consists of an interference pattern formed by coherent superposition of the approximately plane-wave incident beam with the roughly spherical-wave signals scattered by the sample. The holograms were recorded in a Gabor (in-line) geometry. The

Fig. 17. X-ray hologram of several zymogen granules. The figure shows a $19 \times 15 \mu\text{m}$ field of a $200 \times 200 \mu\text{m}$ hologram. The recording is a shallow relief pattern in the x-ray resist and has been shadowed with heavy metal at a glancing angle to give increased contrast. The exposure was about 1 hour, which provided about 10^{12} spatially and temporally coherent x rays of 24.7-Å wavelength. The resist is spun on a thin (1200 Å) window of Si_3N_4 and was consequently observable by transmission electron microscopy, which was the technique used to produce this micrograph. The figure shows great numbers of interference fringes that comprise the hologram and determine its resolution. From the narrowest observable fringe spacing one can infer that sample information on a size scale less than 1000 Å is recorded. [In Collaboration with SUNY, Stony Brook.]

effect is to create patterns reminiscent of a Fresnel zone plate as shown in Fig. 17. The recording process was carried out using a spatially and temporally coherent (1.8 μm coherence length) beam of 24.7-Å x rays. For the sample shown in Fig. 17 the exposure time was 90 minutes. The hologram required approximately 10^{12} coherent photons, and corresponded to a radiation dose of order 200 megarads. After exposure the resist was developed and then metallized to enhance the relief image. The transmission electron micrograph shown in Fig. 17 indicates that information is recorded to a resolution level of about 500 Å. We are now addressing the problem of image reconstruction.

Fig. 18(a). The procedure for performing soft x-ray contact microscopy of biological samples. Image contrast depends on x-ray absorption of biologically important elements.

Fig. 18(b). A soft x-ray micrograph of stained normal red blood cells. An x-ray contact image (carbon-K alpha at 44 Å) of a normal cell has been made onto a resist (copolymer-PMMA/MAA 90:10), which has been magnified (5600 $\times$) by a scanning electron microscope. The resist and blood cells were exposed for 6 hours to the soft x rays. The normal red blood cells were fixed in glutaraldehyde and stained with lead citrate, osmium tetroxide, and uranyl acetate for imaging contrast.

Fig. 19. Student making adjustments to sputtering apparatus used to fabricate high quality multilayer structures for use as moderate bandpass x-ray mirrors. In the vacuum chamber at the left are three magnetron sputtering targets with a substrate rotation stage above. Controls and power supplies are in the background.

Fig. 20. Measured angular response of the reflectivity of a W/C multilayer is compared with a calculated fit. The multilayer consists of 20 layer-pairs of W and C with a period of 42.5 Å. More interface mixing at the W on C compared to the C on W interface is predicted by this fit.

Contact X-Ray Microscopy

Soft x-ray contact microscopy is a high-resolution imaging technique that may also be used to look at biological materials in a living state. The technique has traditionally been used to "write" integrated-circuit patterns. For biological samples, image contrast is due to absorption at the carbon and nitrogen K edges. Figure 18 illustrates the technique. A biological sample is placed on a resist, usually polymethylmethacrylate (PMMA) on a silicon or Si_3N_4 substrate, then exposed to x rays. After development in methyl isobutyl ketone a relief map is obtained that can be viewed by electron microscopy. The resolution of this technique depends on a number of factors, including wavelength, sample thickness, and source size. Typical resolution is about 300 angstroms. Apparatus for use of this technique is now operational in our laboratory. Work with biological samples, mainly sickled and normal red blood cells, has just begun.

Multilayer Mirrors

Facilities for the fabrication and characterization of multilayer structures for use as x-ray optical coatings were active in their first full year of operation. Students played a major role in these developments. Performance of the sputtering system was characterized in many ways. Many materials were sputtered, and their rates characterized, in search of improved material combinations for x-ray optical multilayers. The lateral uniformity of our multilayers was investigated and improved to provide for coating larger areas with more uniform structures. Interfacing of various subsystems of the sputtering apparatus with a computer was begun to better control and monitor the deposition process.

Detailed characterization of multilayer structures is important for a thorough understanding of the limits to their x-ray optical performance. These characterizations take many forms, some of which are performed in-house while others require outside facilities and collaborations. Characterization of multilayers is important, as is an understanding of the limits of performance. Our characterization capabilities in 1986 included a diffractometer capable of measuring multilayer reflectivity at hard x-ray wavelengths (1.54 Å). Measurements at these short wavelengths allows us to sample many orders of multilayer reflectivity, which can then be analyzed to study the composition profiles across the layers. Figure 20 shows a measured performance for one of our tungsten-carbon multilayers and a model fit to the measured reflectivity. This fit is achieved by assuming that the interfaces were not infinitely sharp, and that the W on C interface had a different width than the C on W interfaces.

A new apparatus, described in a later section, is capable of measuring multilayer reflectivities in the longer wavelength region from several angstroms to several hundred angstroms at near normal incidence.

Fig. 21. High resolution transmission electron micrograph along the layers of a Mo/Si multilayer provides a direct image of the quality of the layering process. The silicon wafer substrate and amorphous silicon buffer layer are seen at the bottom right and the Mo layers of the multilayer are the darker of the two layers. The image was obtained at the Center for X-Ray Optics.

Currently this apparatus is equipped with a source for work in the 150-375 angstrom range, an especially interesting region for the development of free-electron and x-ray laser cavity mirrors. We have also initiated a collaboration with LBL's National Center for Electron Microscopy to use their complimentary techniques for visualization of multilayer profiles. An example is shown in Fig. 21. Use of synchrotron radiation scattering techniques to study atomic arrangements within amorphous multilayer samples was also begun.

Several projects involving the use of multilayers for specific applications were initiated in 1986. Multilayer mirrors for x-ray imaging systems were fabricated by our laboratory and were used in a wide variety of experiments, as described previously in this report. The application of multilayers as pre-monochromators in synchrotron beam lines to reduce thermal loads on delicate monochromator crystals was also considered. Monochromator crystals that are used in the spectral region below 2000 eV are generally fragile and need to be protected even from the bending magnet radiation of a modern storage ring such as the NSLS x-ray ring. The Center is providing an experimental optical system to prefilter the radiation used on the X24A (National Bureau of Standards) beamline at NSLS in order to give this protection. The system comprises a water cooled metal substrate coated with a multilayer coating that is suited to the geometry of the beamline, which includes a pivoted downstream section. The multilayer chosen to meet these rather special requirements is a SiC/V structure. The material and parameter choices provide for a narrower filtering passband and better isolation of the Bragg reflection from the specular reflection compared to a conventional high-Z/low-Z combination. These advantages must be traded off against diminished Bragg reflecting efficiency. The overall optimization of the system in the present case leads to a fourfold reduction in power loading on the main monochromator for a tolerable loss of throughput. Even better performance will be achievable in future systems where the geometrical constraints are not determined in advance.

Soft X-Ray Spectroscopy

A major thrust of the Center's technological efforts is the development of tools and techniques for high resolution soft x-ray spectroscopy, based on the use of many x-ray sources, including storage rings, laser-produced plasmas, and x-ray lasers. We have, as examples, proposed high resolution monochromator designs for the Advanced Light Source, designed a high-throughput x-ray monochromator for use with plasma sources, made measurements of molecular x-ray spectra at NSLS, and, in a collaborative effort with the Lawrence Livermore National Laboratory (LLNL), begun efforts to measure x-ray laser line widths. A study of the absolute response of x-ray photographic films has also been completed. Our development of efficient x-ray photocathodes based on thin films of condensed rare gases has provided quantum yields above unity in broader spectral regions than previously possible. Finally, we applied some of our picosecond spectroscopic techniques to measurements of compression and transport in large laser plasma studies at the University of Rochester.

High Resolution Spectroscopy

The increased interest in intense coherent sources of soft x-ray and extreme ultraviolet radiation is motivating the development of new spectroscopic instruments operating in the grazing incidence region 10–500 Å. X-ray holography, photoelectron spectroscopy, and grating microscopy all require monochromators with spectral resolving power $\lambda / \Delta\lambda = 10^3$ to 10^4 , or even higher. Existing spectroscopic instruments are incapable of this performance without severe compromises in other areas. For example, a conventional Rowland circle spectrometer/monochromator using a grating with equidistantly ruled grooves has severe astigmatism (i.e., long spectral lines) and an oblique focal surface requiring a complicated motion to scan wavelength. Other instruments, such as those using toroidal or holographic gratings, fail to achieve simultaneously high resolution, freedom from astigmatism, and an erect focal plane.

Recent advances in grating fabrication now make it possible to vary the groove spacing continuously across the surface. This allows precise correction of the optical aberrations that limit spectral resolution, and makes it possible to construct high resolution spectrometers and monochromators free from astigmatism and with a flat spectral field. Furthermore, the surfaces of the mirrors and gratings in these instruments are simple easily fabricated planes and spheres. Varied-space grating technology has already been exploited in the fields of space astrophysical instrumentation and laboratory plasma spectroscopy, and an instrument for the time-resolved measurement of line widths from the LLNL soft x-ray laser is under construction. The technique will also be valuable in the construction of high resolution instruments for synchrotron radiation beamlines.

High Throughput Soft X-Ray Monochromator

Efficient collection and utilization of the soft x-ray and extreme ultraviolet radiation (30–300 eV) from laser-produced plasma sources often requires a monochromator with high throughput (solid angle acceptance $\times$ efficiency) but only moderate resolution. We have designed, constructed, and tested a novel instrument meeting these requirements. Simple in principle, it uses a spherical grating that rotates about an axis to perform the wavelength scan, while focusing in the sagittal direction is achieved with a pre-mirror set orthogonally to the grating, as shown in Fig. 22. This pre-mirror can be a simple strip of glass, bent to the correct radius. For synchrotron radiation applications, the high throughput feature of this monochromator can be traded for high resolution, leading

Fig. 22. Schematic diagram of a high-throughput monochromator, based on a cylindrical glass "premirror" and spherical, conventionally ruled gratings.

to performance better than that of conventional instruments such as toroidal grating monochromators.

X-Ray Laser Line-Width Measurements

In a joint project with LLNL, we have undertaken a project to measure the time-dependent line width of the Livermore selenium laser (206 and 209 angstroms). The spectral resolution ($\lambda/\Delta\lambda$) required for this experiment is very high—in excess of 10,000. At the x-ray laser wavelength, such resolution is difficult or impossible to obtain using conventional spectroscopic techniques; consequently, we are constructing a special spectrometer (Fig. 23) that uses a varied line space grating, together with crossed mirrors to eliminate astigmatism, forming an image of the emitting region for each spectral line. A picosecond streak camera at the focal plane will be used to examine the time structure of the laser pulse. The resolution of the instrument will be limited by the streak camera to about 10,000. With a higher-resolution detector such as film, the resolution would approach 30,000, but would not reveal time-dependent line narrowing features.

This type of instrument has great potential for achieving high spectral resolution with both bending magnet and undulator radiation at synchrotron radiation facilities. Indeed, some of its practical advantages, which include an erect field, simple scanning mechanism, and use of simple optical surfaces make it appear an attractive alternative to existing monochromator designs. We are undertaking a design study to

Fig. 23. Proposed method for high spectral resolution, time-resolved measurement of x-ray laser line width using a varied line space grating. (In Collaboration with Lawrence Livermore National Laboratory.)

Fig. 24. (a) Secondary electron emission is illustrated. Typically the secondary electron escape depth, λ_e , is small compared to length, $(\lambda_p)^{1/2}$, so that only a small fraction of the secondary electrons are emitted. (b) Preliminary results for the absolute quantum yield of Xe vs. energy. The energy dependence was calculated from the known $\mu(E)$ and fit to a measurement at 1254 eV. Also shown is the measured quantum yield for CsI and Au. [In collaboration with AT&T Bell Laboratories.]

determine the suitability of these advanced optical designs for application at both Aladdin and the Advanced Light Source. Incorporation of such designs in future beamlines will require close collaboration with industry.

Rare Gas Solids as "Super" X-Ray Photocathodes

An on-going effort has been the development of high efficiency photocathode materials for time-resolved measurements in the 100 to 10,000 eV region. In the past few years we have developed accurate models and experimental procedures for the characterization of x-ray photocathodes. We have demonstrated that the alkali halides, particularly cesium iodide, can constitute highly efficient and stable photocathodes at room temperature (10 to 100 times more efficient than earlier photocathodes such as gold). In a collaboration with AT&T Bell Laboratories we have participated in a similar development of condensed rare gas (Xe and Ar) photocathodes, where very long secondary electron escape depths promise high quantum yield photocathodes. Our preliminary results are shown in Fig. 24 for the absolute quantum yield, Y electrons per incident photon, versus photon energy, E . These results indicate that the rare gas solids will have secondary electron yields that are an order of magnitude greater than those of the relatively high efficiency alkali halides. These RGS "super" photocathodes will be of critical importance for measurements of very low level x-ray intensities.

Our present work on the characterization of solid Xe and Ar photocathodes is in collaboration with Eric Gullikson and the AT&T Bell Laboratories.

Characterization of Multilayer X-Ray Analyzers

There has been an historic need in x-ray optics for large-angle mirrors that selectively reflect and analyze the long wavelength x-rays and that complement the grazing-incidence diffraction gratings. An important recent development has been the sputtered/evaporated multilayer mirrors on alternatively high and low atomic-number materials with regular spacing in the 10 to 100 angstrom range that provide strong diffraction intensities at large angles in the 20 to 200 angstrom x-ray region. We are now completing a systematic and detailed study of 25 state of the art multilayer analyzers that have been designed for bandpass reflection in specific x-ray regions for such applications as x-ray monochromators and for selective, high efficiency reflecting optics for x-ray telescopes and x-ray microscopes.

The objective of this study has been to develop relatively simple analytical descriptions of the reflectivity characteristics of these multilayers. We accomplish this by fitting semi-empirical model relations to detailed experimental data for the integrated reflectivity, R , the peak percent reflectivity, P , the angular width, ω and the resolving power, $E/\Delta E$, for the first few orders of diffraction lines (see Fig. 25(a)). We model the multilayers using fixed parameters, the volume of the unit cell, the geometric d-spacing, and fitting parameters Γ_1 , Γ_2 , and α , the fractional thicknesses of the unit cell for the high atomic number layer and of assumed linear transition layers of the heavy element, into the light element regions, where α is an asymmetry factor. We assume linearly varying transition layers that may represent either interface roughness and/or simple diffusion layer characteristics. An example of the output plots for R , P , ω , and $E/\Delta E$ is also shown in Fig. 25(b) for the assumed model.

Picosecond X-Ray Spectrometry of Laser Fusion Targets

Illustrated in Fig. 26 are x-ray intensities versus time for various

Fig. 25. (a) Reflectivity vs. angle for a tungsten-carbon multilayer. The Bragg peak is parameterized by the integrated reflectivity, R , the peak percent reflectivity, P , and the angular width, ω . (b) The energy dependence of R , P , ω , and $E/\Delta E$ is calculated and fit to measurements at a few photon energies spanning the region of interest.

emission lines from a laser-irradiated microballoon target. These spectra were obtained with a picosecond x-ray streak camera and our elliptical analyzer x-ray spectrograph (the SPEAXS system), which is now in use at the OMEGA laser facility at the University of Rochester. Such time-resolved spectral measurements, using layered target techniques, allow the experimental determination of thermal transport and mass ablation rates on spherical targets by the emergence of various spectral line intensities versus time. These results are of considerable importance to the development and understanding of energy absorption and transport in inertial fusion implosion experiments.

Response of X-Ray Films

The most often applied position-sensitive detection technique in x-ray optics is photographic film. We have developed relatively simple two-parameter models for the accurate absolute characterization of x-ray

Fig. 26. The x-ray emission spectrum vs. time for a laser-irradiated microballoon obtained with an x-ray streak camera and our elliptical x-ray spectrograph. [In collaboration with the University of Rochester.]

films. Last year work was completed on the development of efficient analytical relations and new experimental calibration methods for their evaluation in the region of 100 to 1000 eV. We have just extended this to analytic models and experimental procedures for the absolute characterization of x-ray films for the 1000 to 10,000 eV region. Illustrated here in Fig. 27 is an example of the description by a single universal analytical model relation (smooth curves) of the density versus exposure data for 930 eV and 8050 eV photons normally incident upon the new Kodak two emulsion x-ray Direct Exposure Film (DEF).

Molecular X-Ray Spectroscopy

X-ray emission and absorption spectroscopy permits detailed

Fig. 27. The cross section of a DEF emulsion imaged by SEM. The model used to calculate the response of the film is illustrated. The calculated density vs. exposure is fit to data taken for 930-eV and 8050-eV normally incident photons.

study of the electronic structure of molecules. In particular, synchrotron radiation promises the capability of studying the electronic states of individual elements within compounds and alloys, and of impurities, clusters, and minor constituents embedded in solid systems. X-ray emission spectroscopy has already been used to study dilute metal alloys, rare gas solids, and fragile compounds that are damaged by electron excitation. Molecular x-ray spectra are rich in overlapping strong and weak structural details arising from the complex atomic environment of the molecule.

Recently, Cl-K β emission and Cl-K absorption spectra from Freon 11, 12, and 13 were measured at NSLS. These molecules are of particular interest because of their suggested role in the chemistry of the upper atmosphere. For the first time, an x-ray emission spectrum of a molecule was obtained solely with excitation below the ionization threshold.

Synchrotron Radiation Projects

Fig. 28. A water-cooled mirror, installed for testing on the X-17 undulator beamline at NSLS. This mirror will be permanently installed on the X-1 beamline, and a second will be used on the 54-pole wigglers beamline at SSRL.

Since its inception the Center has been host to the Laboratory's programs in synchrotron radiation optical systems. This activity has included extensive engineering programs involving the design of beamlines and beamline components for facilities now operating or soon to be built. During the past year, we continued to put significant effort into the design and testing of components that can tolerate high x-ray fluxes—fluxes high enough to melt or badly distort common mirrors and crystals. A water-cooled copper mirror that can absorb several kilowatts of power has been delivered to Brookhaven's National Synchrotron Light Source (NSLS) and is now in use with its new X-17 soft x-ray undulator, as seen in Fig. 28. A second system will be installed soon on the new VUV branch of Beamline VI at the Stanford Synchrotron Radiation Laboratory (SSRL). At a more fundamental level, studies of thermally loaded mirrors and crystals, including finite-element computational modeling and measurements of actual temperature contours, were conducted at both SSRL and Cornell. We have designed a new high-resolution spherical grating monochromator for use at SSRL as well as future facilities such as the Advanced Light Source.

The thermal load associated with the intense photon beams available from new insertion device beamlines imposes very demanding requirements on focusing elements and monochromators. The total thermal power and the localized heat density from these new synchrotron sources can easily distort mirror surfaces and significantly reduce monochromator performance. During the last year, we measured temperature contours on the first crystal of the LBL-Exxon-SSRL wiggler beamline at Stanford, one of the world's most intense synchrotron radiation sources. We conducted similar measurements at Cornell's CHESS facility. To aid in the design of these systems, we have developed computer programs that calculate photon power distributions produced by wiggler and undulator sources, power losses in various beamline components (graphite filters and beryllium windows), temperature distributions on mirrors and monochromator crystals, and resultant stresses and surface distortions of optical elements.

These computer programs were used in the design of water-cooled mirrors for both the X-1 beamline at NSLS, and the VUV branch of the LBL-Exxon beamline at SSRL. At SSRL the peak absorbed power density on the optical surface of this mirror is expected to be 5.2 W/mm^2 . An analysis of the water-cooled mirror indicates that the maximum surface slope error due to thermal distortion will be acceptable at less than $300 \text{ } \mu\text{rad}$ in the sagittal direction. Each mirror was fabricated using a dispersion-strengthened copper alloy for high strength and high thermal conductivity. The polished surface of chemically plated nickel has irregularities of less than 10 angstroms rms, which minimizes x-ray scattering.

The high flux from insertion device beamlines also demands new monochromator designs. Accordingly, we are developing a high-resolution spherical grating monochromator that will also be used on the VUV branch of Beamline VI at SSRL (Fig. 29). Special attention is being given to the factors that influence the resolving power of the monochromator: optical aberrations, fabrication tolerances for the spherical gratings, distortions due to thermal stresses in the grating, and stability and alignment of the overall slit-grating-slit triangle. This work requires establishing new standards for figure and microroughness tolerances. At LBL we carry out tests on the quality of witness samples and delivered end products, making microroughness and flatness measurements and performing thermal cycling tests. Thermal distortions are a particular

Fig. 29. Schematic drawing of the actively cooled grating used in the spherical grating monochromator and a photograph of a model of this component. The kinematic mounting system provides sub-arcsecond adjustment of the grating in ultra-high vacuum.

concern. For this reason, we have used direct water-cooled metal grating substrates to minimize thermal deformation. This is the first time this technique has been applied to a soft x-ray monochromator.

Our participation in the development of beamlines for SSRL also continued throughout 1986. Our effort on the VUV branch of the 54-pole wiggler beamline (Beamline VI) is now well under way, and incorporates the developments in optical component and monochromator design already mentioned.

Advanced Light Source Activities

The Center was involved in the Advanced Light Source program in three main areas: the scientific program, insertion devices, and beamlines. We consider these separately, although they are closely related.

The Center has long been active in promoting and organizing the ideas of the intended light source user community, and this activity came to a major focus during FY 1986 with the November 1985 Users Workshop held in the Berkeley Conference Center. This gathering gave an authoritative statement of the community's need for a soft x-ray synchrotron radiation source and provided valuable documentation of the scientific direction and technological requirements of the program.

Once the basic character of the ALS was established, it became possible to study the technical possibilities for providing the highest quality radiation beams. These are generated mainly by tunable undulators. The first attempt to define the initial complement of insertion devices following the workshop was designed to cover the entire spectral range of interest with five insertion devices: four undulators and a wiggler. Anticipated performance of these devices with regard to spectral brightness, photon flux, and coherent power are found in the section on Undulators and Wigglers for the Advanced Light Source at the beginning of this report. Center personnel devised specific designs for these sources and worked out schemes for realization of the magnetic structures and conceptual designs for the engineering of the mechanical systems. Studies of the required quality, mechanical accuracy, tuning speed, photo power output, etc., were carried out to show that this set of devices was compatible with the storage ring environment and capable of delivering the kind of soft x-ray beams that earlier calculations had promised. In carrying out this work the Center was able to call on its wide experience in designing and fabricating these kinds of structures. This general effort will continue and expand as plans for the scientific program are refined.

In view of the extremely wide variety in the user community and its interests, the initial schemes for beamlines concentrated on showing that very general purpose optical systems could be designed that provided in one beamline the capability for all possible choices in the resolution-flux trade-off. This study was carried out using only flat and spherical surfaces to guarantee that surface fabrication accuracy would be the best attainable. A series of schemes was developed that provided, on paper at least, an unprecedentedly high resolution and a unique capability to accept the entire photon beam from the source without loss due to phase space mismatch. This latter capability, unequaled anywhere, is possible for 10- μ m spectrometer slits, which give, for example, a resolving power of 10^4 at the oxygen edge. This kind of optical performance depends on the outstanding emittance properties of the source. The Center staff worked out specific beamline configurations for each insertion device and verified their theoretical performance by exact computerized ray tracing. They are continuing to study these design questions and are also proving their ideas in practice by building prototype systems for use at the SPEAR storage ring. There is also an ongoing program of studies and design work that has already solved problems of photon beam thermal loading that are more severe than those anticipated at the new light source.

Magnet Structures for Undulators and Wigglers

Fig. 30. Cutaway elevation of the SSRL Beamline X wiggler currently under construction at LBL and photograph of the nearly complete wiggler.

Significant effort in 1986 went into the conceptual design of the five candidate insertion devices for the Advanced Light Source. The foundation of this effort, however, was an ongoing program that has produced a number of insertion devices for operating facilities and a succession of technological design innovations, some now part of operational wigglers and undulators, some still conceptual. The latest of our designs to reach the fabrication stage is a neodymium-iron wiggler intended as the source for Beamline X at SSRL. This insertion device has 15 periods, each 12.8 cm long, and will achieve 1.40 T at the 2.1-cm operating magnet gap.

The magnetic structure, support and drive system, and vacuum system for the Beamline X wiggler is shown in Fig. 30. Neodymium-iron was selected as the permanent-magnet material because it has a 16% higher coercive force than rare earth-cobalt, it chips less, it is easier to bond to common materials, and it is less expensive. The basic building block of the magnetic structure is a half-period pole assembly, each of which includes an electromagnetic coil that is used to correct the wiggler vertical field integral.

Looking beyond such designs, we continued to design still better undulators and wigglers for use in synchrotron light sources and free-electron lasers. A most promising approach is to incorporate permanent-magnet material into electromagnetic undulators or wigglers in such a way that the magnetic field that can be produced is as large as (or larger than) the field produced with short-period permanent-magnet insertion devices.

In addition, the most recent embodiment of this concept is general enough to be applicable to, for example, quadrupole magnets, as well as wigglers and undulators. The basic idea is the following: If one goes from the useful field volume of an electromagnet deeper and deeper into the coil slot, one finds that more and more magnetic flux enters the iron, leading to debilitating saturation of the iron when the structures are small. However, by breaking the coil up into a number of sections, and by placing appropriately magnetized permanent-magnet blocks between the coil

sections, one can take magnetic flux out of the iron, thus preventing saturation. This basic design concept is illustrated in Fig. 31

Fig. 31. Cutaway view of a dipole magnet based on a "laced electromagnet" design. The permanent-magnet material (dotted) is placed so as to remove flux from the iron pole piece, thus preventing saturation of the iron.

A new course, Introduction to X-Ray Physics (Physics 198), was offered during 1986 in the Physics Department at the University of California, Berkeley. This course emphasized modern developments in the physics, technology, and applications of soft x rays. Open to both undergraduate and graduate students, topics included generation of x rays with laboratory tubes, synchrotrons, black-body radiation, and laser-plasma sources; concepts of coherence and partial coherence, with examples at visible and x-ray wavelengths; techniques for the generation of partially coherent radiation at extreme ultraviolet and x-ray wavelengths, including laser harmonics and mixing techniques, x-ray lasers, and relativistic electrons interacting with periodic magnet structures (undulators); x-ray interaction with matter, atomic scattering factors, and the relation to refractive index; reflective optics, imaging systems, microscopes and telescopes; interference coatings; diffractive optics, gratings, and zone plates; resolution of imaging and dispersive systems; uses of crystals; zone plate x-ray microscopy resolved to 500 Å; element-specific applications, coherence requirements, and the relation to undulators and interference coatings; x-ray interferometry with crystals, gratings, and interference coatings; and, finally, application to plasma physics, short-wavelength lasers, biology and medicine, and material and chemical sciences.

A separate graduate seminar, the Soft X-Ray Physics Seminar (290R), was also given to supplement the Physics 198 lectures. This brought many good outside speakers to the campus and to the Center. Students working in the Center received research assignments related to the above subjects, worked closely with a member of the scientific staff, and in some cases co-authored published scientific papers. A likely outgrowth of these activities is the emergence of a new interdisciplinary program in Applied Science and Technology within the UC Berkeley College of Engineering.

Student Training Activities

Fig. 32. University of California students from Physics 198—"Introduction to X-Ray Physics"—while attending the nearby conference on "Short Wavelength Coherent Radiation: Generation and Applications." Several students presented papers that were later published in an American Institute of Physics conference proceedings.

Fig. 33. Some of the students who worked on various projects within the Center for X-Ray Optics during 1986.