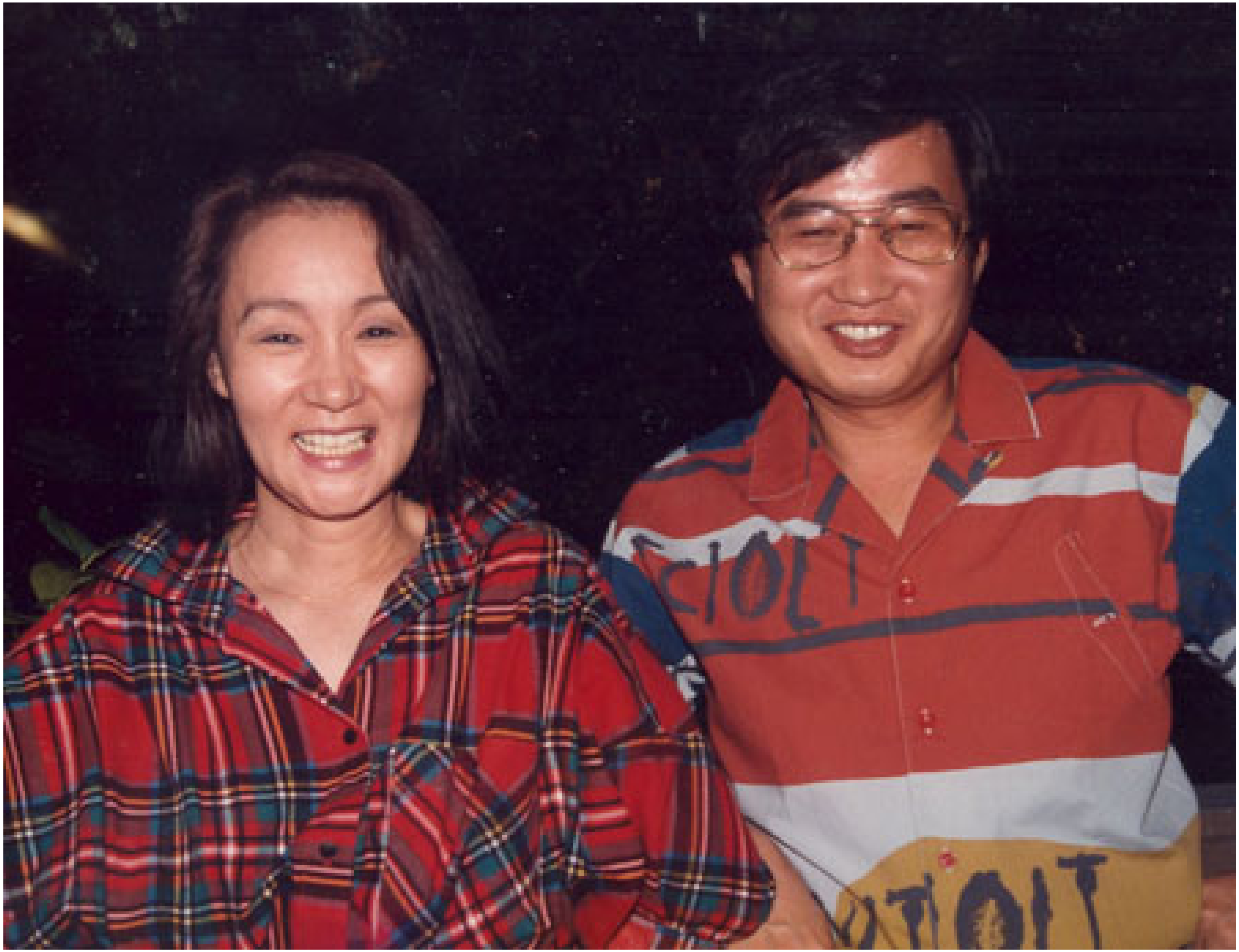
Brightness and Coherence Research at the Center for X-Ray Optics

David Attwood
University of California, Berkeley

Happy days in Berkeley

Happy Couple: Kwang-Je and Kyeong-Hwa aka Elizabeth



The Impossible Dream- The ALS in Berkeley

Happiness delayed

Center for X-Ray Optics (CXRO) formed, Fall 1983

LBL Starts World's First Center For X-ray Optics

By Lynn Yarris

The only one of its kind in the world, LBL's new Berkeley Center for X-Ray Optics is scheduled to begin full operation in April, as part of the Accelerator and Fusion Research Division.

Under the leadership of physicist David Attwood, research at the new Center will focus on the use of radiation that falls between x-rays and ultraviolet light (about 10 keV to 10 eV) on the electromagnetic spectrum—often referred to as XUV radiation.

"The Center will serve as a national source of development and application of new techniques for the use of XUV radiation," says Attwood. "Emphasis will be placed on emerging technologies, such as diffractive and reflective optics, necessary for the efficient transport, dispersion, focusing and detection of XUV radiation from synchrotron and other light sources."

The relatively unexplored XUV spectral region has been called the last frontier of the electromagnetic spectrum. According to Attwood, "After a 30-year dormancy, interest in the region has suddenly come alive."

The reason for this renaissance, he says, is a rapid advancement in technological capabilities, permitting exciting new applications of XUV radiation and optics in the fields of physics, chemistry, materials science, and the biological and life sciences.

Potential applications include the development of x-ray microscopes that could provide detailed views of materials and biological structures, such as cells, never before attainable, and the production of much smaller microcircuits for the electronics industry than is currently

In addition, says Attw devices, such as LBL' Advanced Light Source, vide tunable, coherent that would revolutioniz opportunities in this sp

which is so rich in atomic resonance structure."

The idea of a center specializing in the study of XUV radiation through x-ray optics was first proposed at the June 1981 Monterey Conference on Low-Energy X-Ray Techniques, sponsored by the American Institute of Physics.

Organized by Attwood and University of Hawaii physicist Burton

currents LAWRENCE

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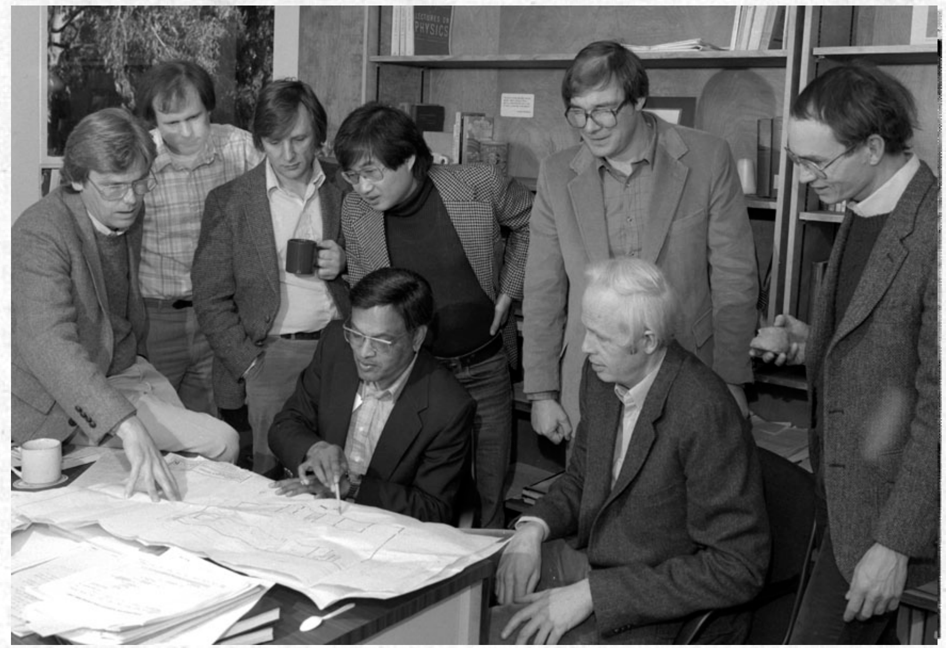
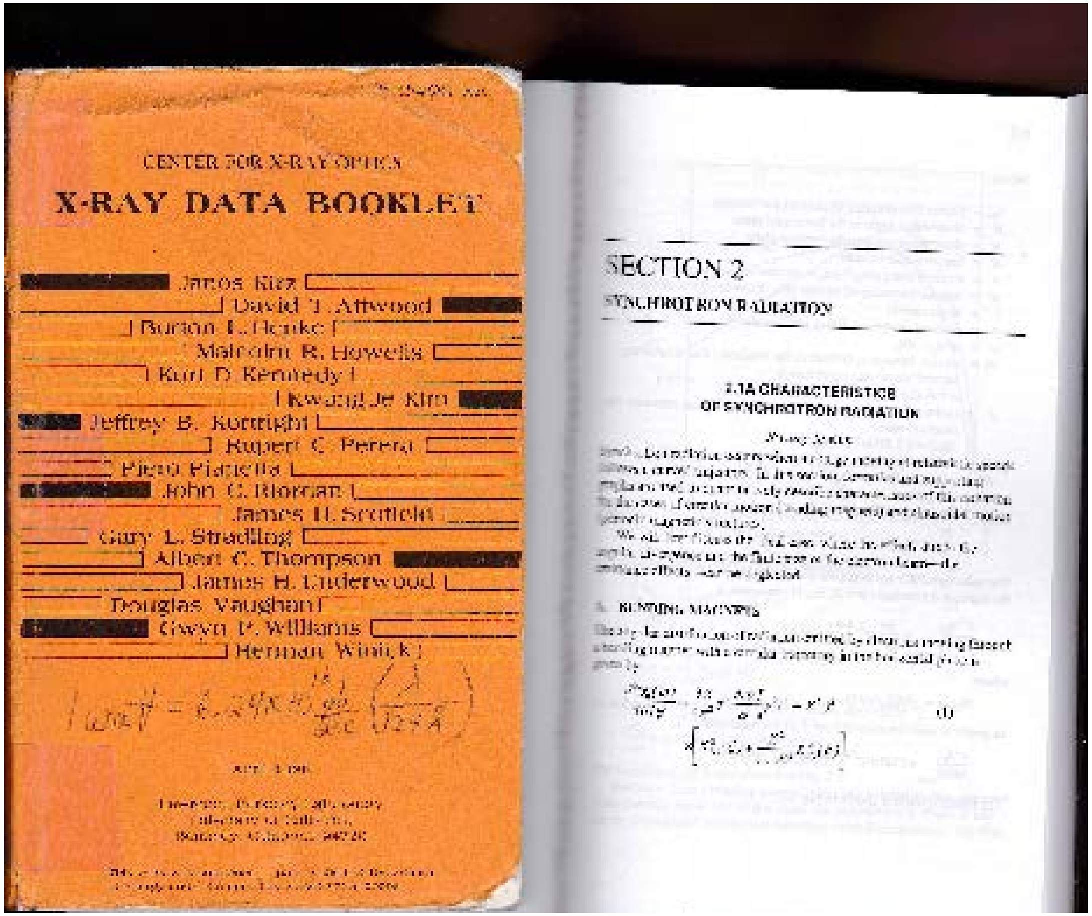
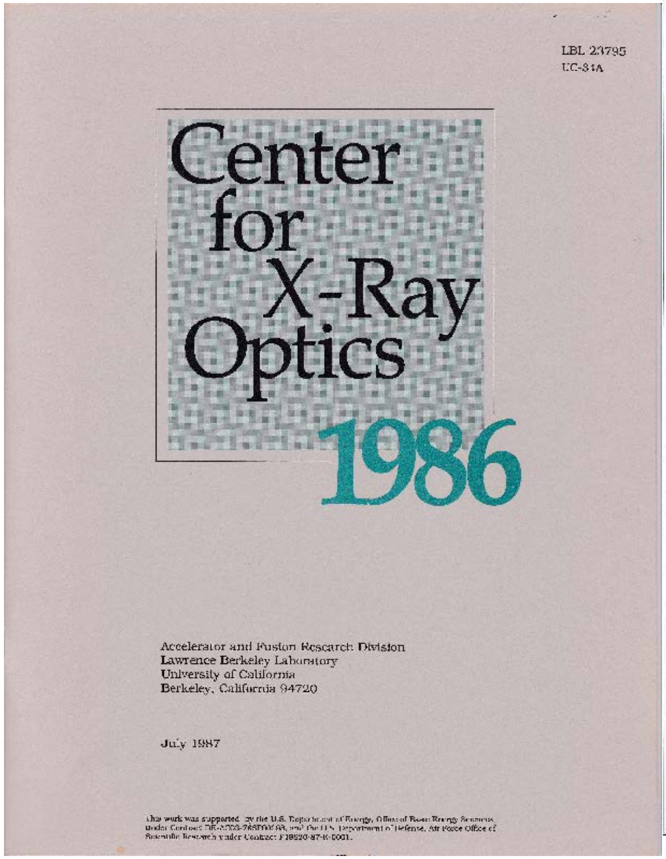


Vish More of Plant Engineering (center, at desk) describes the laboratory facilities which will soon be available at LBL's new Center for X-ray Optics. Behind More are, from left to right, David Attwood, consultant Gary Sommargren of Zygo Corporation, James Underwood, Kwang-Je Kim, Malcolm Howells and Al Thompson.

Orange Data Book, April 1986



Center for X-Ray Optics, LBL



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UC-34A

Center for X-Ray Optics 1986

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

July 1987

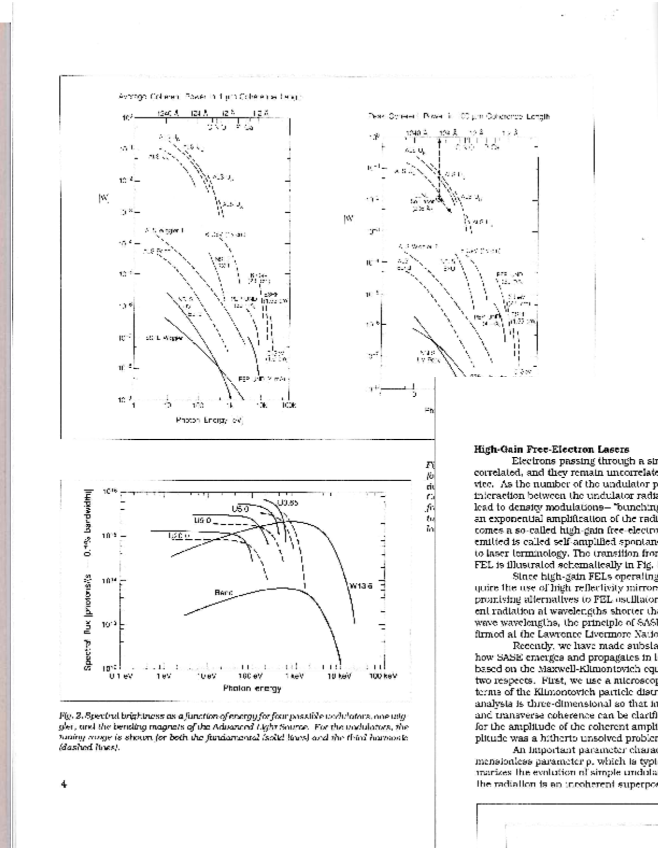
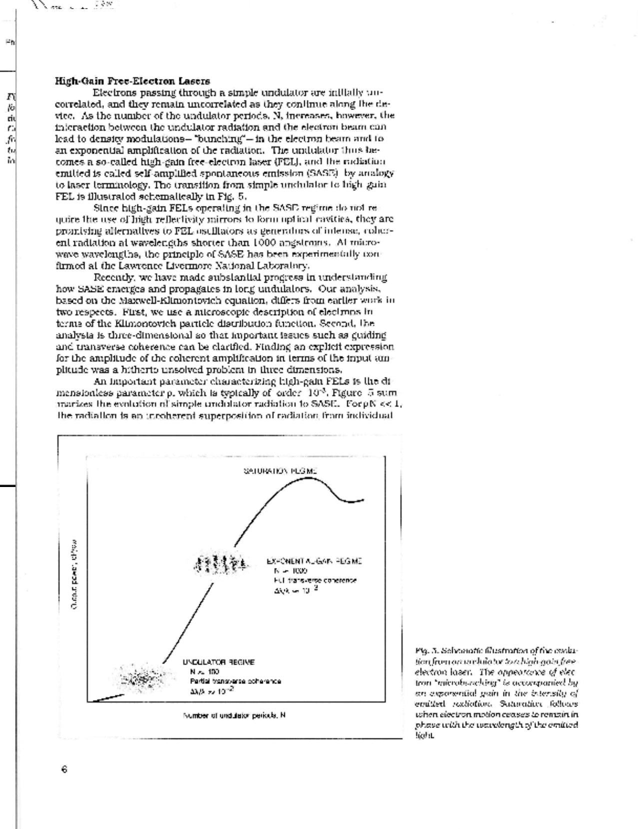


Fig. 2. Spectral brightness as a function of energy for four possible undulators, one wiggler, and the bending magnets of the Advanced Light Source. For the undulators, the tuning range is shown for both the fundamental (solid lines) and the third harmonic (dashed lines).

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.

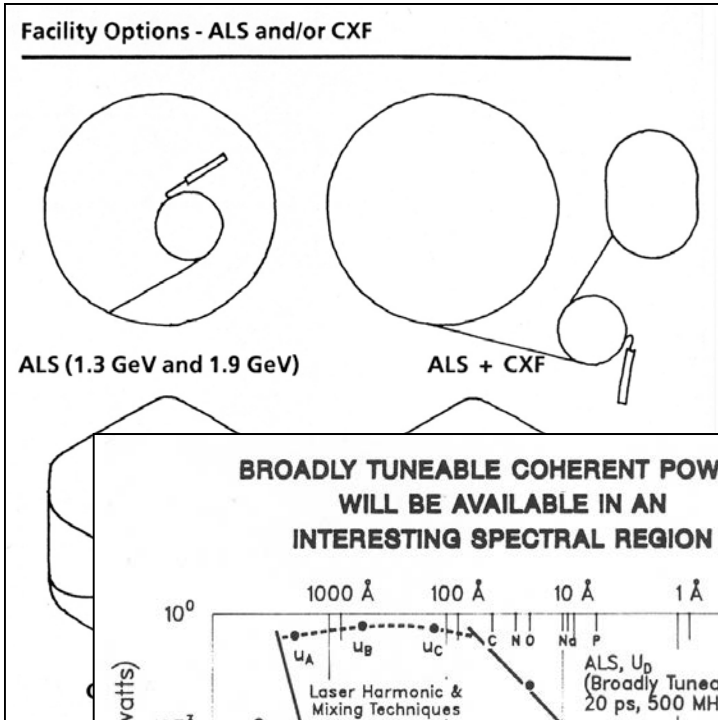
Recently, we have made substantial progress in understanding how SASE emerges and propagates in long undulators. Our analysis, based on the Maxwell-Klimontovich equation, differs from earlier work in two respects. First, we use a microscopic description of electrons in terms of the Klimontovich particle 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.

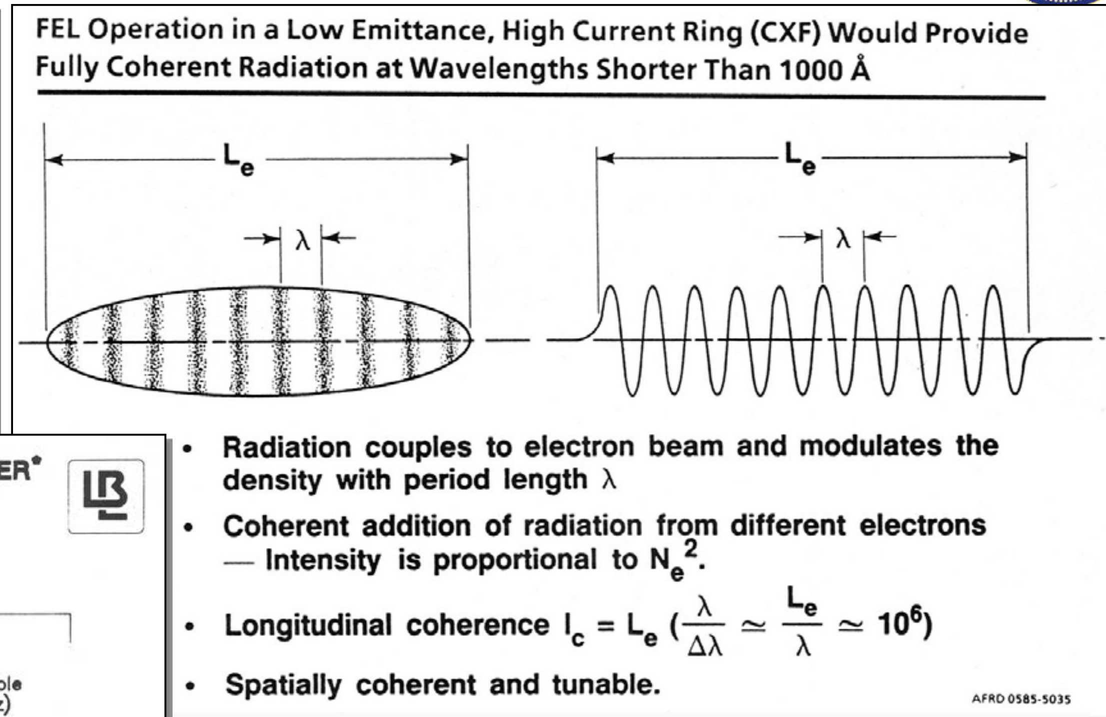
An important parameter characterizing high-gain FELs is the dimensionless parameter ρ, which is typically of order 10^{-3}. Figure 5 summarizes the evolution of simple undulator radiation to SASE. For ρN << 1, the radiation is an incoherent superposition of radiation from individual

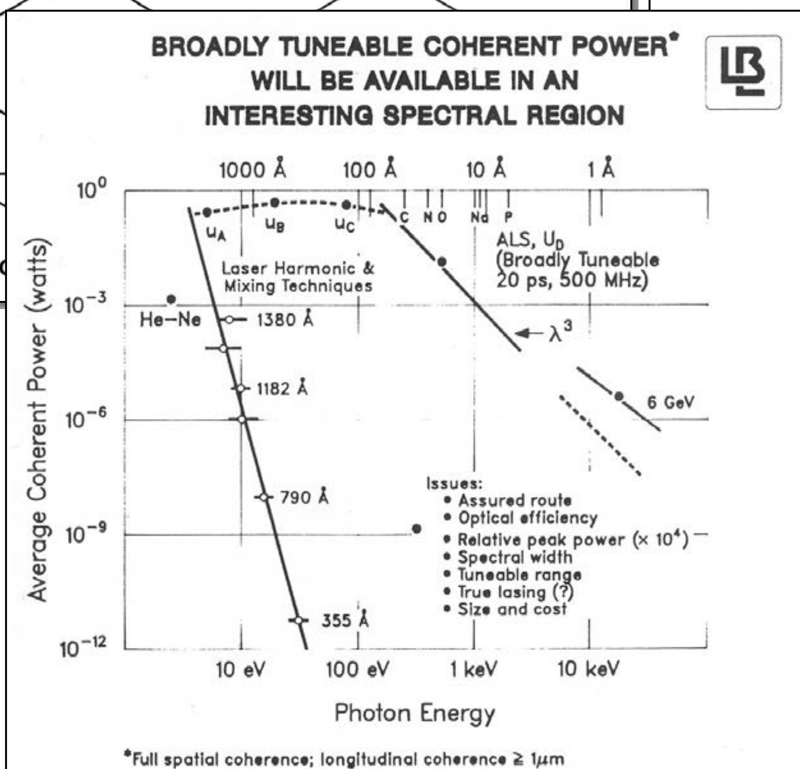
Fig. 5. Schematic illustration of the evolution from an undulator to a high-gain free electron laser. The appearance of electron "microbunching" is accompanied by an exponential gain in the intensity of emitted radiation. Saturation follows when electron motion ceases to remain in phase with the wavelength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

6

Kwang-Je Kim's FEL designs

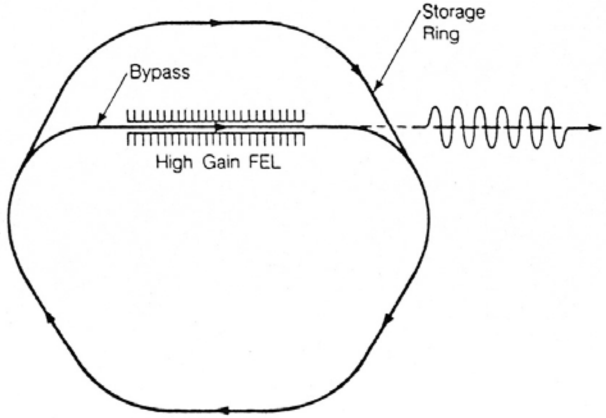






Kwang-Je Kim's FEL designs

High-Gain, Single-Pass Free Electron Laser

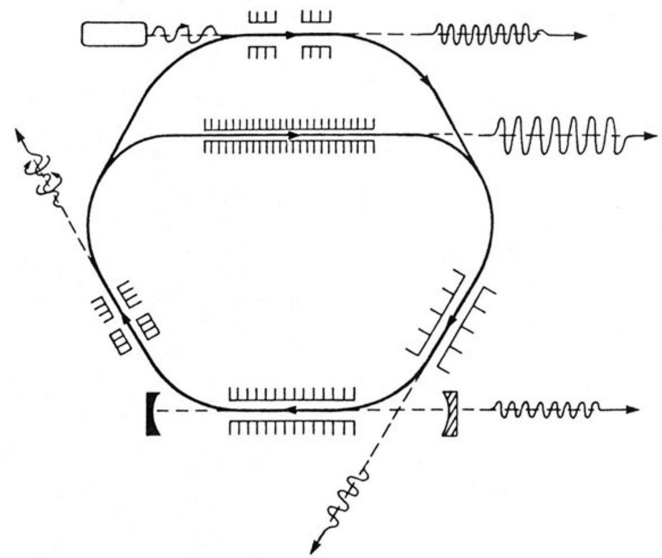


- FEL interaction is so strong that an intense, coherent signal develops from noise in a single pass.
  - — Mirrors are not required.
- Long undulator (~20 m; 500–1000 periods) with small gap (~3 mm) requires bypass operation.
- Tens of megawatts of peak power is expected.

An FEL Community White Paper Was Organized

Coherent X Rays and Vacuum-Ultraviolet Radiation from Storage-Ring-Based Undulators and Free Electron Lasers

December 1984



A New Scientific Case for the ALS
Based On Coherence and Nanoscale Science

14 June 1985, Volume 228, Number 4705 **SCIENCE**

June 1985

Tunable Coherent X-rays

David Attwood, Klaus Halbach, Kwang-Je Kim

The spectral region referred to as the XUV includes soft x-rays and ultraviolet radiation. Photon energies in this region extend from several electron volts (eV) to several thousand electron volts (keV). The primary atomic resonances of elements such as carbon, oxygen, nitrogen, and sodium, as well as resonances from many molecular transitions, appear in this region. In addition, the photon wavelengths in this region match important spatial scales such as the pitch and diameter of biochemical helices, the microstructural features of materials, and the dimensions of the next generation of electronic microcircuits.

which emit radiation of longer wavelengths. Optical techniques, including reflection, dispersion, and imaging, suffer from photoelectric absorptive effects in this region. Between the wavelengths of about 10 and 1000 angstroms (Å) there are no materials that are both transmissive and capable of supporting an atmosphere of pressure over macroscopic dimensions.

Summary. A modern 1- to 2-billion-electron-volt synchrotron radiation facility (based on high-brightness electron beams and magnetic undulators) would generate coherent (laser-like) soft x-rays of wavelengths as short as 10 angstroms. The radiation would also be broadly tunable and subject to full polarization control. Radiation with these properties could be used for phase- and element-sensitive microprobing of biological assemblies and material interfaces as well as research on the production of electronic microstructures with features smaller than 1000 angstroms. These short wavelength capabilities, which extend to the K-absorption edges of carbon, nitrogen, and oxygen, are neither available nor projected for laboratory XUV lasers. Higher energy storage rings (5 to 6 billion electron volts) would generate significantly less coherent radiation and would be further compromised by additional x-ray thermal loading of optical components.

Substantial progress in the development of x-ray optical techniques has been made recently (*1–6*), largely as the result of the need for ever smaller microfabrication capabilities in the electronics industry, research on x-ray emitting, hot

resolution, initially developed to study energy transport in hot dense plasmas (*9*), are now commercially available.

In order to extend scientific and technological opportunities, a bright source of tunable, partially coherent, XUV radiation is needed. Coherence, in the limited sense used here, refers to the ability to form interference patterns when wave fronts are separated and recombined. Partially coherent radiation is capable of producing clear interference patterns (fringes), but only within limited transverse or longitudinal displacement (*10*). The longitudinal displacement within which fringes can be formed is called the coherence length ℓ_c (*11*), which is given by the wavelength λ times the number of waves of coherence $\lambda/\Delta\lambda$ (spectral purity): $\ell_c = \lambda^2/\Delta\lambda$.

For experiments that utilize phase-sensitive techniques, such as x-ray interferometry and x-ray microholography, a radiation field with full spatial coherence and several micrometers (μm) of longitudinal coherence is often satisfactory.

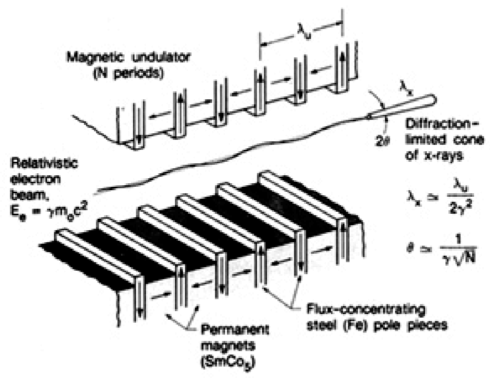


Fig. 1. Partially coherent x-rays are produced when a thin, pencil-like beam of relativistic electrons traverses a periodic magnetic structure. The radiation is relativistically contracted to short wavelengths and condensed to a narrow forward cone.

November 1985 ALS workshop

Don Stevens
Judy Bostok
Klaus Halbach
Martha Krebs
Yuan Lee

Workshop Report December 1985

PUB-5154
December 1985

Report of the Workshop on an
Advanced Soft X-Ray and
Ultraviolet Synchrotron Source:
Applications to Science and Technology
November 13-15, 1985
Berkeley, California

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

ALS is in the budget

State of the Union: Reagan Reports to the Nation

Transcript of President's Speech to Congress on State of Union

Following is a transcript of President Reagan's State of the Union Message to Congress last night, as recorded by The New York Times:

The New York Times/Jose R. Lopez

CHEERING THE CHIEF: President Reagan being applauded by Vice President Bush and Speaker Thomas P. O'Neill Jr. before speech.

The American dream is a song of hope that rings through the night winter air. Vivid, tender music that warms our hearts when the least among us aspire to the greatest things — to venture a daring enterprise; to unearth new beauty in music, literature, and art; <u>to discover a new universe inside a tiny silicon chip or a single human cell.</u>

LBL’s World Class Accelerator Team (AFRD) Designs a State-Of-The-Art Low Emittance Machine

Director’s Technical Review of the Advanced Light Source

February 18-19, 1986 February 1986

Advanced Light Source Overview
Klaus H. Berkner

Photon Performance of ALS
Kwang-Je Kim

Storage Ring Design and Performance
Max Cornacchia

Advanced Light Source Injection System
Michael S. Zisman

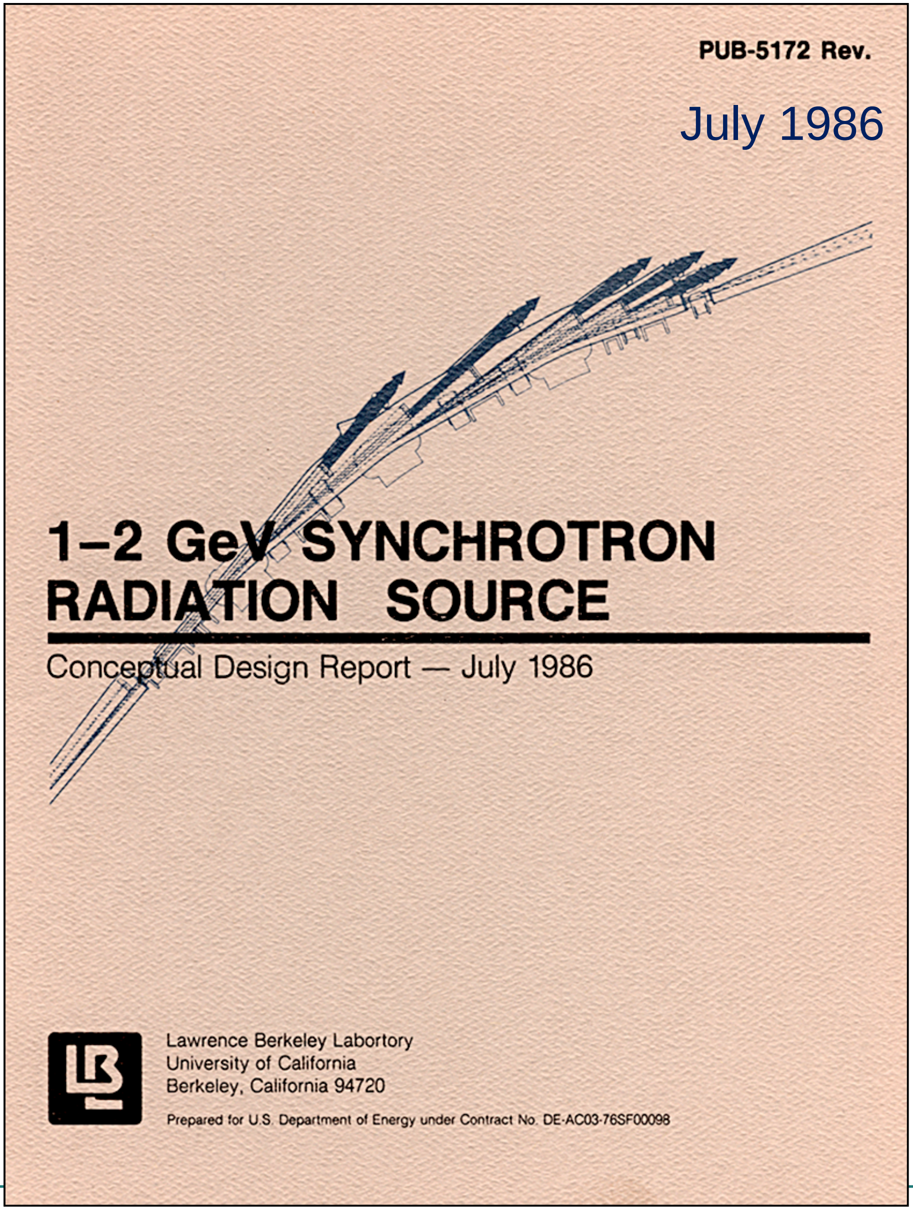
ALS Vacuum System
Kurt Kennedy

Study of Chamber Impedance
Glen Lambertson

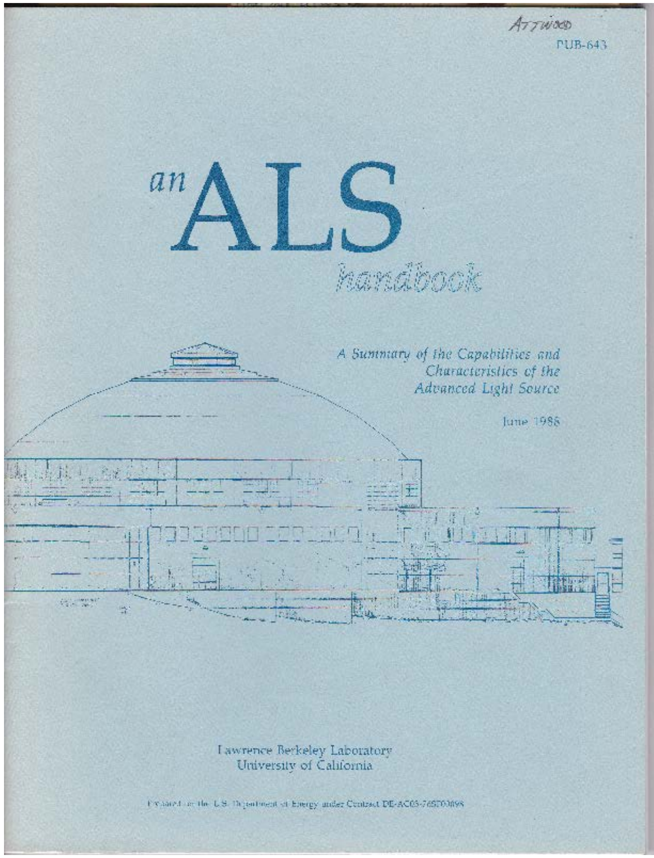
Magnet System Design and Performance
R.T. Avery

Control, Feedback & Power Systems
Henry Lancaster

ALS Program and R&D Issues
Jay Marx



ALS Handbook June 1988



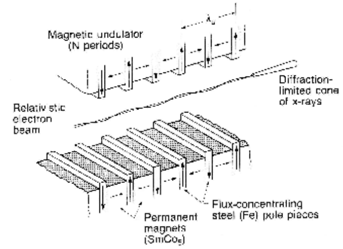


Fig. 2-1. Schematic of a periodic magnet structure (an undulator) of period λ_u and with a number of periods, N. The oscillations of the electron beam passing through the structure produce ultraviolet and soft x-ray radiation (photons) of high spectral brightness and high coherent power.

$$B_0 = 3.33\exp\left[-\frac{g}{\lambda_u}\left(5.47 - 1.8\frac{g}{\lambda_u}\right)\right] \quad \text{Samarium–Cobalt} ,$$

where g is the full magnetic gap [Halbach, 1983].

2.3 Optical Characteristics of Synchrotron Radiation

The radiation spectrum from a bending magnet is smooth, centered around the critical frequency ω_c. Wigglers can be regarded as a sequence of bending magnets of alternating polarity. Thus, its radiation characteristics are similar to those from bending magnets, apa

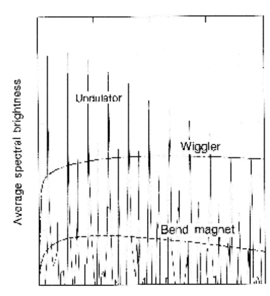


Fig. 2-2 Harmonic content of undulator radiation arising from interference of radiation from different periods.

2.3.1 Bending-Magnet Radiation. The angular distribution of radiation emitted by electrons moving through a bending magnet, with a circular trajectory in the horizontal plane, is given by

$$\frac{d^2\mathcal{F}_B(\omega)}{d\theta d\psi} = \frac{3\alpha}{4\pi^2}\gamma^2\frac{\Delta\omega}{\omega}\frac{I}{e}y^2(1+X^2)^2 \times\left[K^2_{2/3}(\xi) + \frac{X^2}{1+X^2}K^2_{1/3}(\xi)\right], \quad (2\text{-}14)$$

where

P_T[kW] = 0.633 E^2[GeV]B_0^2[T]L[m] I[A].

For bending magnets, B_0^2 in the above expression must be replaced by $2B^2$, where B is the magnetic field in the bending magnet. The angular distribution of the radiated power is

$$\frac{d^2P}{d\theta d\psi} = P_T\frac{21\gamma^2}{16\pi K}G(K)f_K(\gamma\theta,\gamma\psi), \quad (2\text{-}40)$$

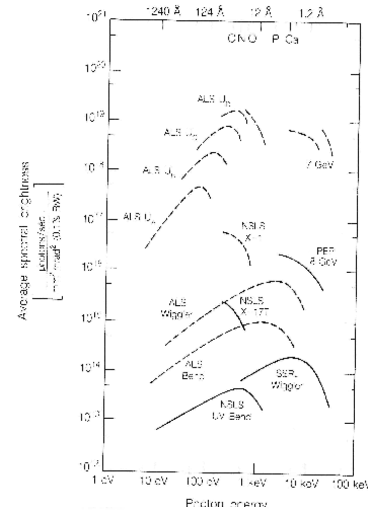
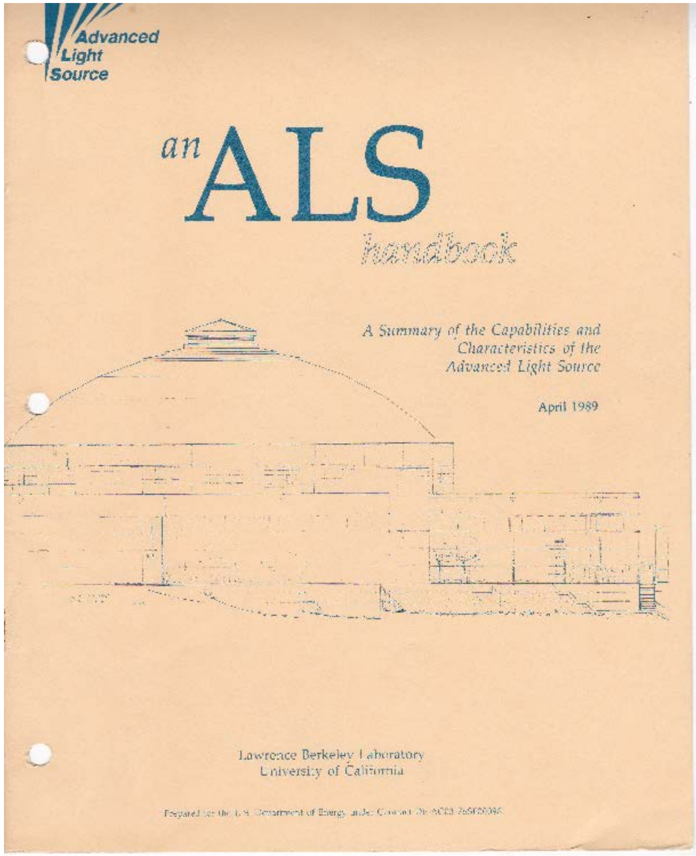


Fig. 2-11. Aver of photon energ

ALS Handbook April1989



20

and for samarium-cobalt magnets by

$$B_0 = 3.33 \exp\left[-\frac{g}{\lambda_u}\left(5.47 - 1.8\frac{g}{\lambda_u}\right)\right] \quad 0.07 < \frac{g}{\lambda_u} < 0.7 \ , \tag{3-13}$$

where g is the full magnetic gap [Halbach, 1983]. These equations apply directly to wiggler designs, where the emphasis is on achieving a high peak field. For undulators, the deflection parameter K is more important, and the optimum magnetic design differs from that of a wiggler. Although there is no known universal function for the undulator field strength, a conservative engineering design results in peak fields approximately equal to 0.95 times the values derived from Eqs. (3-12 and 3-13).

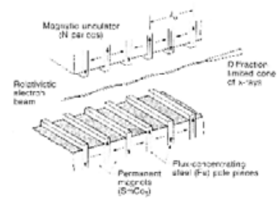


Fig. 3-1. Schematic drawing of a periodic magnet structure (an undulator) of period λ_u and with a number of periods, N. The oscillations of the electron beam passing through the structure produce ultraviolet and soft x-ray radiation (photons) of high spectral brightness.

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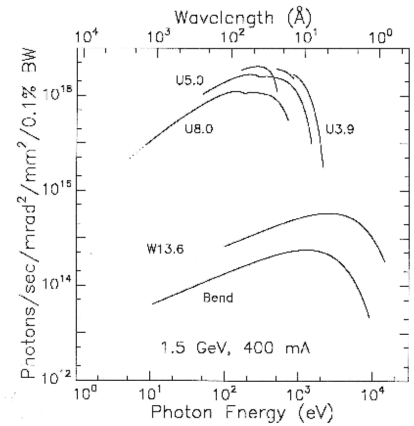


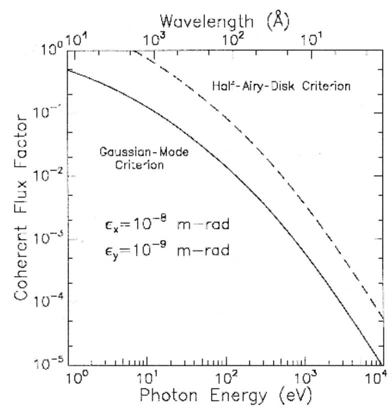


Fig. 4-4. Fraction of the flux that is transversely coherent by the single-Gaussian-mode criterion [$\mathcal{F}_c/\mathcal{F}_0$ of Eq. (3-28)] (solid line) and by the half-Airy-disk criterion (dashed line), over the spectral range of the three undulators of Table 4-1.

45

...b. Undulator U5.0.

I(Amp)	SIGX(mm)	SIGY(mm)	SIGPX(mr)	SIGPY(mr)	N	LAMBDW(cm)	XLEN(m)
0.400	0.330	0.063	0.030	0.016	95	5.00	4.9

K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))	PCEN(W)
0.05	0.01	2.83E−04	2.32E−00	1.64E−02
n	EP(keV)	F(#/s,0.1%BW)	FDEN2	BRI
1	4.77E−01	1.24E+13	1.24E+15	1.31E+16
3	1.78E+00	2.54E+07	5.69E+09	4.34E+10
5	2.13E+00	5.59E+01	1.42E+04	1.09E+05
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))	PCEN(W)
0.50	0.11	3.20E−02	1.85E+02	1.40E+00
n	EP(keV)	F(#/s,0.1%BW)	FDEN2	BRI
1	3.80E−01	1.18E+15	1.55E+17	1.17E+18
3	1.14E+00	2.37E+13	5.11E+15	3.90E+16
5	1.90E+00	5.21E+11	1.30E+14	9.91E+14
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))	PCEN(W)
1.20	0.26	1.84E−01	3.80E+02	5.21E+00
n	EP(keV)	F(#/s,0.1%BW)	FDEN2	BRI
1	2.48E−01	3.69E+15	3.72E+17	2.79E+18
3	7.45E−01	8.88E+14	1.60E+17	1.24E+18
5	1.24E+00	2.47E+14	5.48E+16	4.16E+17
K	B0(T)	PTOT(kW)	PDEN2(W/(mr**2))	PCEN(W)
3.82	0.82	[illegible]	1.75E+03	6.03E+01
n	EP(keV)	F(#/s,0.1%BW)	FDEN2	BRI
1	5.15E−02	3.37E+15	1.55E+17	1.06E+18
3	1.55E−01	3.39E+15	2.45E+17	1.81E+18
5	2.58E−01	2.67E+15	2.77E+17	2.08E+18

Characteristics of Synchrotron Radiation 1989

Page 565-632, AIP Conference Proceedings 184, "Physics of Particle Accelerators,"
M. Month & M. Dienes ed., AIP 1989 (COMP)

CHARACTERISTICS OF SYNCHROTRON RADIATION

Kwang-Je Kim

Center for X-ray Optics
Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory, Berkeley, CA 94720

TABLE OF CONTENTS

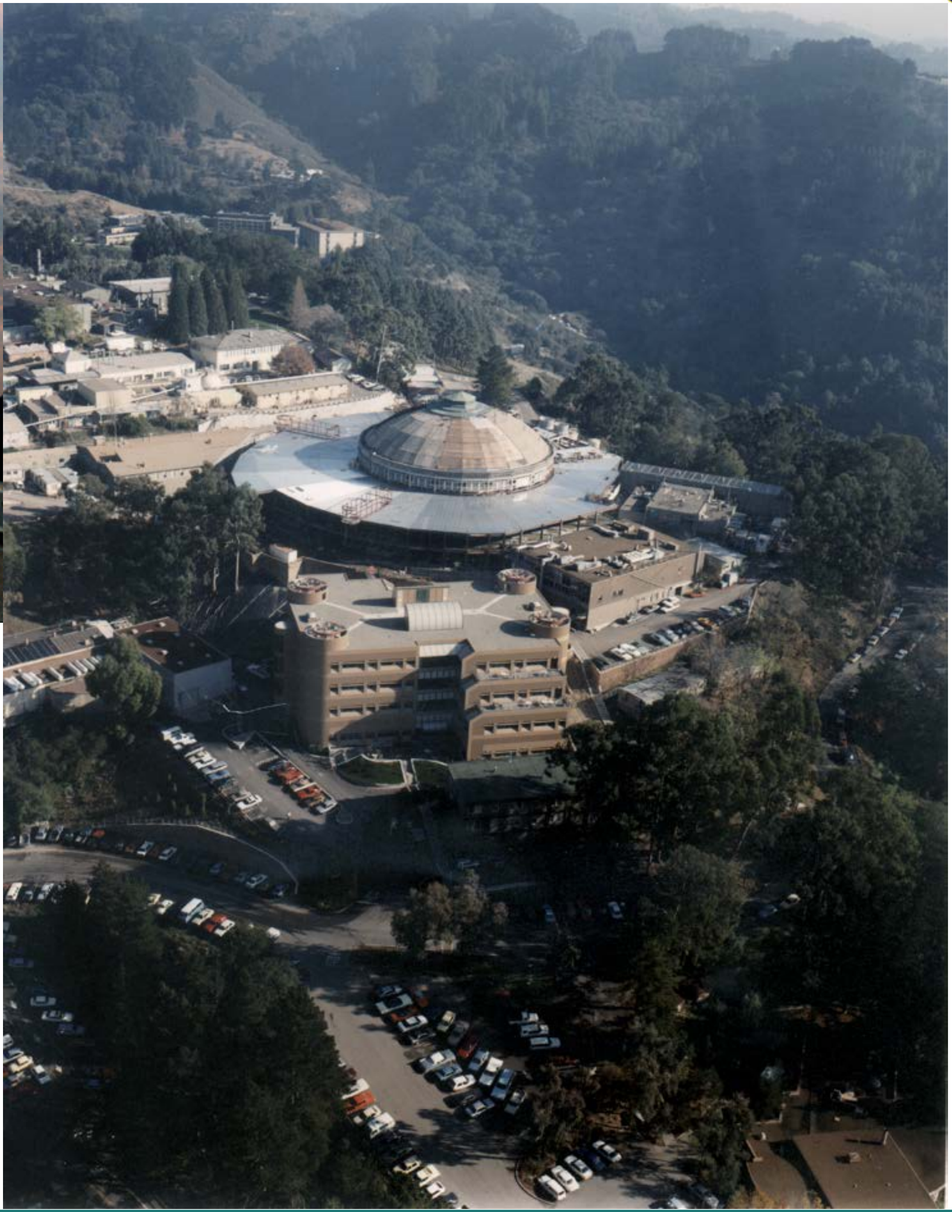
Kwang-Je Kim, "*Characteristics of Synchrotron Radiation", pp. 565-632,*

in US Particle Accelerator School

M. Month and M. Dienes, Eds.

AIP Conference Proc. **184,** 565 (1989)

ALS Construction Begins, 1988



First Light at the ALS, October 4-5 1993

October 8, 1993 • Vol. 21 • No. 39

LBL CURRENTS

Lawrence Berkeley Laboratory • Berkeley, CA 94720

ALS produces first light

By Lynn Yarris

The Advanced Light Source, LBL's newest, largest, and most technologically advanced accelerator, produced its first experimental light this week. During a Tuesday afternoon ceremony to mark the occasion, a phosphor-painted target glowed bright orange when it was struck by a beam of white x-ray light from bending-magnet port 10.3. Many of the people who made the moment possible watched the event on a video monitor.

The actual first light from the ALS came at 11:34 p.m. the previous night (Oct. 4), when the beamline was put through its final preparatory tests. Word of the success Optics (CXRO), led the development of the beamline, which will serve as a fluorescent x-ray microprobe available for use by LBL groups to study material, biological, and geological samples. He opened Tuesday's ceremony by thanking the staffs of the ALS and the CXRO, as well as LBL Materials Sciences Division (MSD) Director Daniel Chemla and acting ALS scientific adviser Phil Ross, who helped obtain funding for the beamline which came from the U.S. Department of Energy's Division of Materials Science in Germantown, Md.

"We're all celebrating this day!" Thompson enthused.

Bending-magnet port 10.3 features the longest beamline the concurrent running of independent experiments. For now, the single branch will be used by Thompson and his CXRO collaborators, Jim Underwood, Karen Chapman, Phil Batson, Ron Tackaberry, Drew Kemp, and Steve Klingler to study trace elements in materials.

The ALS x-ray microprobe is capable of simultaneously detecting and measuring the presence of elements from potassium to zinc in amounts as small as a millionth of a billionth of a gram. Its first use will be to analyze the distribution of trace elements in ceramic materials in an effort to answer the age-old mystery of why ceramics are so brittle. This experiment is a collabora-

Best wishes to Kwang-Je on his 75th birthday