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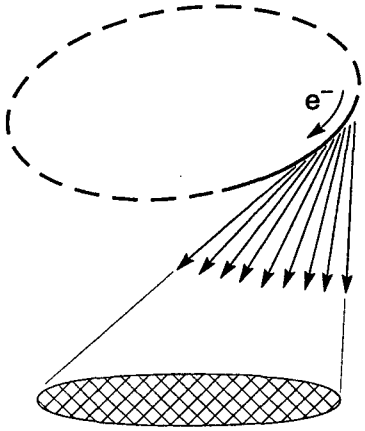
Soft X-Ray Lithography at Berkeley's Advanced Light Source



Proceedings of the Workshop
January 15, 1991

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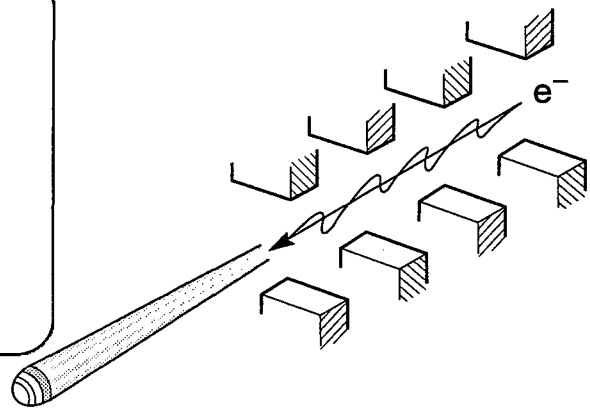

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Soft X-Ray Lithography at Berkeley's Advanced Light Source

Proceedings of the Workshop

January 15, 1991

at

Berkeley, California

***

John Carruthers (Intel)
William Oldham (UC Berkeley)
David Attwood (LBL/UC Berkeley)

Louise Millard, Conference Coordinator
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Foreword

A workshop on soft x-ray lithography (2-200nm radiation) was organized around the relevant capabilities of a unique combination of resources: the Advanced Light Source (ALS) at Lawrence Berkeley Laboratory; the contiguous UC Berkeley campus; and the broad industrial base in nearby Silicon Valley. It is generally believed that developments in x-ray optical techniques will eventually be required as part of the industrial base for nanostructure patterning. The ALS is a national user facility, which will have unique properties of brightness, partial coherence, and spectral coverage ideally suited for x-ray lithography and related research.

A specific objective of the workshop has been to acquaint the semiconductor lithography community with the capabilities, timelines, and availability of the ALS as a national user facility. A related objective was to use the workshop as an opportunity for LBL to learn from the lithography community about its needs, and together fashion an effective strategy for developing an advanced manufacturing technology in the U.S. To give the broadest possible consideration to the issues, speakers were invited who have made major contributions in various kinds of x-ray lithography. They were asked to express their views on the long term technology challenges associated with reduced dimension imaging. Copies of their viewgraphs are reproduced here.

As an outgrowth of the workshop, a consensus emerged on three key issues. First, that the x-ray lithography community needs both a bending magnet and a high-brightness undulator. These will provide: a metrology and registration station; an easy access facility for basic component, resist and mask testing; and sophisticated testing of optics, coatings, defects, optical systems, and more advanced aspects of soft x-ray lithography not yet clearly identified. Second, the timeline for research activities at the ALS (1993) is well matched to industrial needs for advanced pattern transfer below 0.15 microns in the time frame 2000, and beyond. Third, to develop production technology for reduced dimension structures, a supporting infrastructure will be required for masks, optical coatings, resists, synthesis and processing. This infrastructure should be available to the community in a location contiguous to the x-ray test facilities.

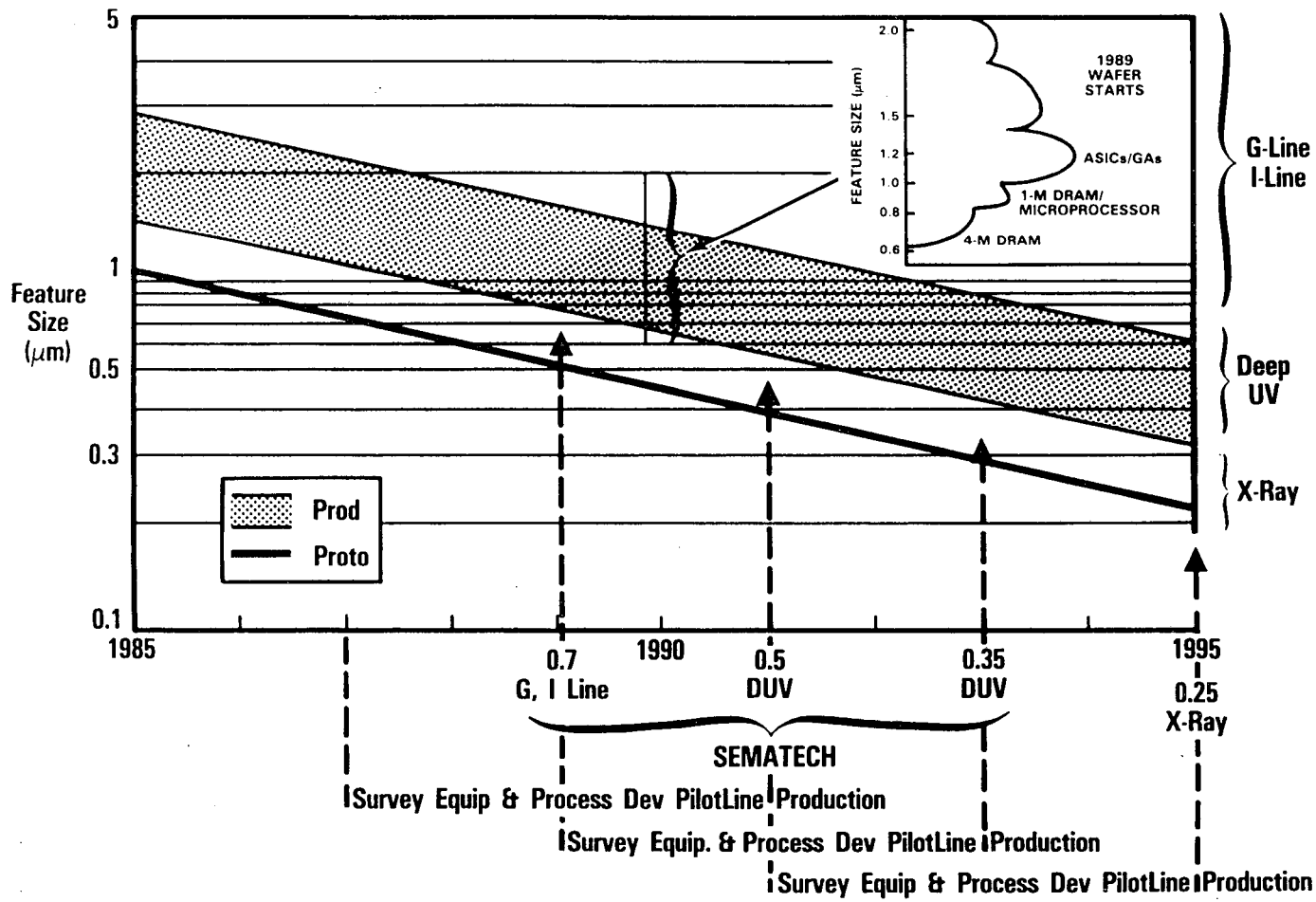
X-RAY LITHOGRAPHY

DARPA
DEFENSE MANUFACTURING OFFICE

DAVID O. PATTERSON
(202) 694-1351

XRL-22

IC LITHOGRAPHY
PRE-PRODUCTION ACTIVITY SEQUENCE



XRL-48
1591-3-13-89-2
R12-1-89

GOAL

TO DEVELOP DOMESTIC INDUSTRIAL BASE FOR X-RAY LITHOGRAPHY FOR PRODUCTION OF INTEGRATED CIRCUITS WITH FEATURES OF 0.25μm AND BELOW

1070-8-24-88-7
R3-26-90

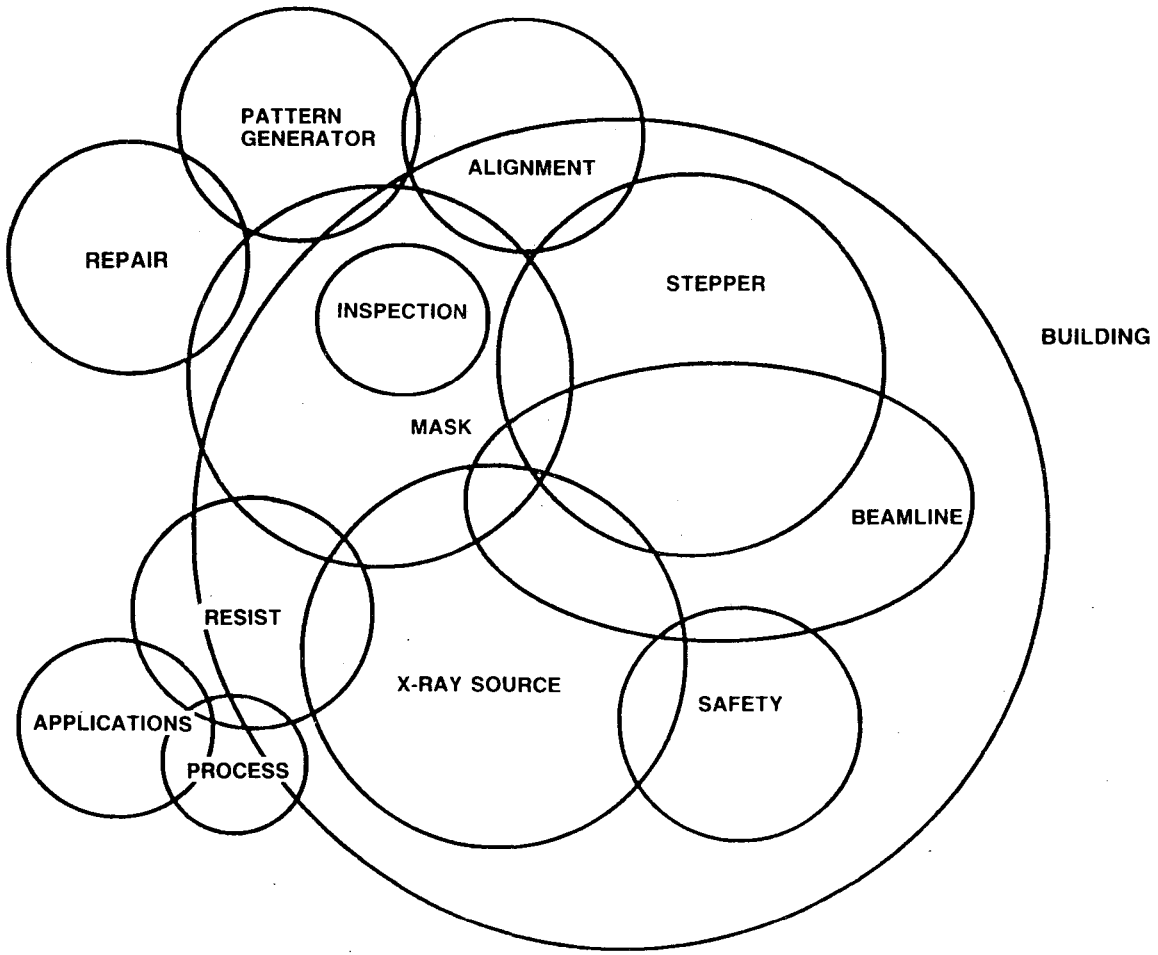
X-RAY LITHOGRAPHY APPROACH

- Develop processing for masks and wafer fabrication
- Establish domestic suppliers for key equipments and materials
- Promote synchrotron technology transfer from national labs to equipment manufacturers
- Promote IC industry access to synchrotrons
- Demonstrate X-Ray lithography in device fabrication

XRL - 14

1070-8-24-88-6

X-RAY LITHOGRAPHY IS A SYSTEM



REF: IBM

XRL-68
808-6-15-90-3

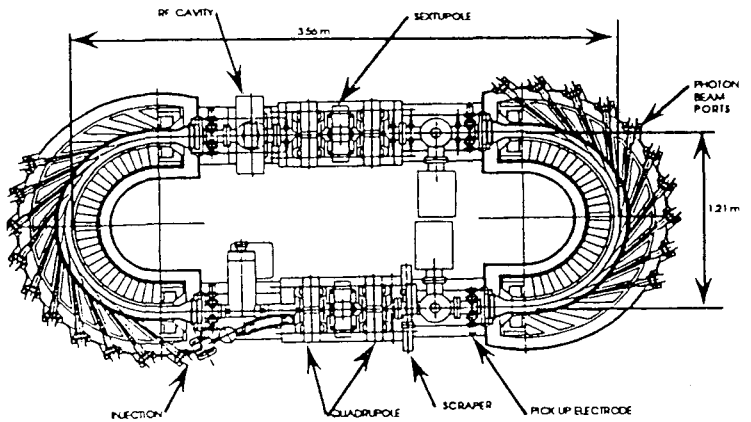
X-RAY LITHOGRAPHY PROGRAM PLAN

PHASE	1988	1989	1990	1991	1992	1993	1994
MASK TECHNOLOGY	SUBSTRATE TECHNOLOGY						
		E-BEAM PG		0.25 PROTOTYPE 0.25 PRODUCTION			
		INSPECT/REPAIR/METROLOGY					
	MASK VENDOR						
X-RAY SOURCES	COMPACT SYNCHROTRON DESIGN/BUILD						AT SEMATECH
		BEAM LINE/ALIGNER					
		INDUSTRY USE OF WISC SYNC					
	PLASMA SOURCES (HIGHER INTENSITY)						
	RESIST (SENSITIVITY, PRODUCTIZATION)						
PROCESS INTEGRATION	0.5 DEVICE, GaAs			0.35			0.25
			PROCESS INTEGRATION				
					MANUF. IMPROVEMENTS		
						TECH TRANSFER	
PROJECTION				MATERIALS, SOURCES, OPTICS			

LITH 113

BROOKHAVEN NATIONAL LABORATORY
SYNCHROTRON DEVELOPMENT

SYNCHROTRON



PROJECT GOALS

- CONSTRUCT SUPERCONDUCTING DIPOLE SYNCHROTRON SPECIFICALLY DESIGNED AS AN X-RAY LITHOGRAPHY SOURCE WITH SMALL FOOTPRINT AND SIMPLE OPERATION
- TRANSFER SYNCHROTRON TECHNOLOGY TO INDUSTRY (DESIGN, CONSTRUCTION, COMMISSIONING AND OPERATION)

APPROACH

- CONSTRUCT NORMAL DIPOLE MACHINE TO INVESTIGATE ACCELERATOR PHYSICS AND INJECTION PARAMETERS OF VERY SMALL SYNCHROTRONS
- INSERT ACCURATELY MEASURED SUPERCONDUCTING DIPOLES INTO WELL-UNDERSTOOD ACCELERATOR LATTICE
- TEAM WITH INDUSTRIAL PARTNER WORKING ALONGSIDE BNL GROUP

ACCOMPLISHMENTS

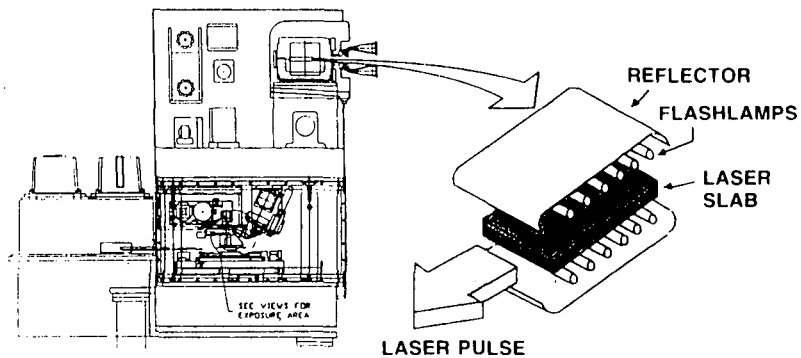
- NORMAL DIPOLE SYNCHROTRON IN ASSEMBLY STAGE
- ENGINEERING OF SUPERCONDUCTING DIPOLE AND INVESTIGATION INTO ITS EFFECTS ON BEAM QUALITY ARE UNDER WAY
- CONTROL SYSTEM IS OPERATIONAL
- INDUSTRIAL PARTNER ON BOARD AND TECHNOLOGY TRANSFER IN FULL PROGRESS

XRL-86

808 1 5 90 19
R7 19 90

HAMPSHIRE INSTRUMENTS POINT SOURCE/ALIGNER

THE SERIES 5000 EXPOSURE TOOL



PROJECT GOALS

- $\leq$0.5 MICRON IMAGING CAPABILITY
- CONCOMITANT MASK FABRICATION TECHNOLOGY
- PILOT-LINE THROUGHPUT: $\geq$10 WLPH (6 IN. DIAM.)
- PRODUCTION THROUGHPUT: $\geq$25 WLPH (6 IN. DIAM.)

APPROACH

- USE LASER PLASMA X-RAY SOURCE ($\sim$14A)
- DEVELOP HIGH DUTY CYCLE LASER SYSTEM
- USE TAILORED SOFT X-RAY SPECTRUM FOR OPTIMUM RESIST EXPOSURE
- DEVELOP SILICON MEMBRANE-BASED MASK TECHNOLOGY

ACCOMPLISHMENTS

- FIRST STEPPER DELIVERED TO AT&T
- BROAD PROCESS LATITUDE DEMONSTRATED IN RESIST EXPOSURES
- 0.5-MICRON MASK FABRICATION TECHNOLOGY DEMONSTRATED
- ALIGNMENT $<0.1\ \mu m$

XRL-81

1801-7-19 90 2
R10 4 90

PLASMA X-RAY SOURCES

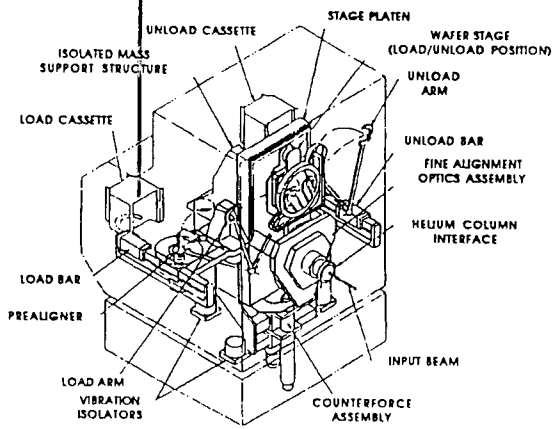
- LASER
  - MORE CONVENTIONAL SIZE, COST THAN SYNCHROTRON
  - LOWER POWER → THROUGHPUT IS MARGINAL
  - HAMPSHIRE INSTRUMENTS MODEL 5000 – DELIVERY IN 90?
  - MICROWAVE IC FABRICATION
  - LIMITATION IN FEATURE SIZE?
  - FUTURE IMPROVEMENTS
    - POWER SUPPLY
    - COLLIMATION
    - DIODE LASER
- GAS DISCHARGE
  - UNDER CONSIDERATION
  - PROMISE OF HIGH FLUX

XRL-52

808-4-18-89-30

SVG LITHOGRAPHY SYSTEMS ALIGNER FOR SYNCHROTRON

ISOMETRIC VIEW OF A SYNCHROTRON ALIGNER



PROJECT GOALS

- TO BUILD A STEP-AND-REPEAT LITHOGRAPHY SYSTEM FOR THE SYNCHROTRON
- TO HELP WITH ITS INTEGRATION AT THE UNIVERSITY OF WISCONSIN CENTER FOR X-RAY LITHOGRAPHY
- TO SUPPLY COMMERCIAL SYSTEMS FOR PRODUCTION OF ICs WITH 0.25-μm FEATURES

APPROACH

- ADAPT X-RAY STEP-AND-REPEAT AND OTHER TECHNOLOGIES TO A VERTICAL ALIGNER
- USE MODULAR HARDWARE AND SOFTWARE DESIGN TO MEET THE DEMANDING SCHEDULE
- PROVIDE AUTOMATION TO ACHIEVE MAXIMUM THROUGHPUT, LITHOGRAPHIC PERFORMANCE, AND RELIABILITY
- ACHIEVE ON-SCHEDULE SYSTEM FUNCTIONALITY THROUGH EFFECTIVE INTERFACE CONTROL WITH THE BEAMLINE AND SYNCHROTRON AT THE UNIVERSITY OF WISCONSIN

ACCOMPLISHMENTS

- DEMONSTRATED 0.15-μm ALIGNMENT ON PREVIOUS XSAR CONTRACT
- HAVE DESIGNED MASK HOLDER COMPATIBLE WITH "STANDARD" MASK CONFIGURATION

XRL-84

1801 / 19 90 4

XRL MASKS

- MASKS: THE BIGGEST CHALLENGE IN X-RAY LITHOGRAPHY
- PROBLEM AREAS:
  - MEMBRANE/ABSORBER – MATERIALS AND PROCESSING
  - PATTERN WRITING – E-BEAM
  - INSPECTION (+ METROLOGY)
  - REPAIR
- ACTION: DEVELOPMENTS IN ABOVE AREAS
  ESTABLISH COMMERCIAL VENDOR

XRL-50

808-4-18-89-28

XRL MASK SHOP
DRAFT STATEMENT OF WORK

GOAL: PROVIDE A RELIABLE SOURCE OF X-RAY MASKS FOR FIVE YEARS

SOW

- STUDY PHASE — DETAILED STUDY OF NEEDS/APPROACHES
  — EVALUATE EQUIP/PROCESSES DEVELOPED IN XRL PROGRAM
- MASK DELIVERY

		1990	1995
"PRODUCTION"	FEATURE	0.8 μ	0.35 μ
	NO. TRANS	1 M	16 M
	EXP. FIELD	2.5 cm	5 cm
"PROTOTYPE"	FEATURE	0.5	.25
	NO. TRANS	250 K	1 M
	EXP. FIELD	1 cm	2 cm
COST		$15K	$7.5K

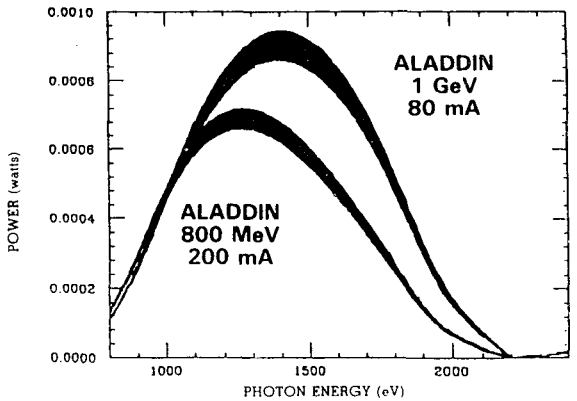
- OPERATION — JOINT OPERATION WITH OPTICAL MASK PRODUCTION
  — TIMELY DELIVERY OF QUALITY PRODUCT
  — IMPORT NEW TECHNOLOGY

LITH-118

1801 7 19 90 1

UNIVERSITY OF WISCONSIN
SYNCHROTRON TEST BED

U. OF WISC. BEAMLINE SPECTRA



PROJECT GOALS

- PROMOTE THE DEVELOPMENT OF X-RAY LITHOGRAPHY WITH SYNCHROTRON RADIATION SOURCES
- PERFORM RESEARCH AND DEVELOPMENT IN THE AREAS OF XRL MANUFACTURING PROCESS
- PROVIDE ACCESS TO SYNCHROTRON FOR SEMICONDUCTOR INDUSTRY

APPROACH

- UTILIZE ALADDIN SYNCHROTRON
- IMPROVE FACILITIES (CLEAN ROOM, DIAGNOSTICS)
- JOINT EFFORT WITH SEMATECH/SRC CENTER OF EXCELLENCE IN XRL

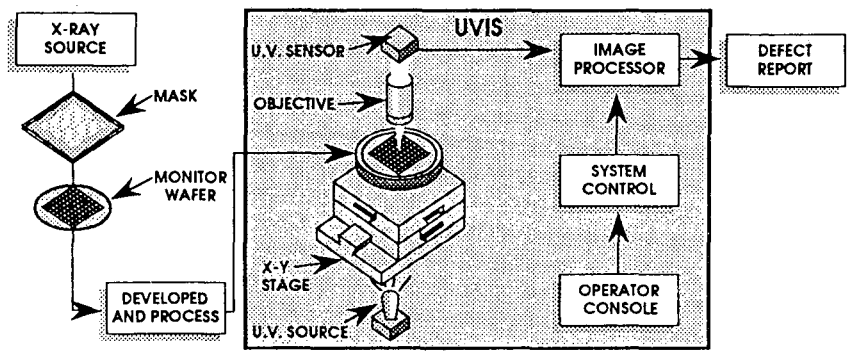
ACCOMPLISHMENTS

- BEAMLINE DESIGN COMPLETED
- CLEAN ROOMS AND EQUIPMENT IN ORDER (APPROXIMATELY 185 SQUARE METERS)
- STAFF AND MANAGEMENT IN PLACE (5 FACULTY, 6 TECH STAFF, 1 VISITING SCIENTIST, 7 GRADUATE STUDENTS AND 3 ADMINISTRATIVE SUPPORT)

XRL- 88
808-1-9-90-2

KLA
MASK INSPECTION SYSTEM

X-RAY MASK INSPECTION



PROJECT GOALS

- COMMERCIAL X-RAY MASK INSPECTION SYSTEM
- 0.1 μM DEFECT DETECTION
- 0.25 μM FEATURE SIZE
- INSPECTION TIME OF 10 MIN./SQ. CM. - EXTENDABLE TO HIGHER THROUGHPUT
- COMPATIBLE WITH MICRION MASK REPAIR SYSTEM
- NEXT GENERATION FOR OPTICAL MASK INSPECTION

APPROACH TO ACHIEVING GOALS

- DEEP U.V. TO ACHIEVE RESOLUTION (SENSITIVITY) AND THROUGHPUT
- INSPECT MONITOR WAFER TO VALIDATE MASK IMAGE

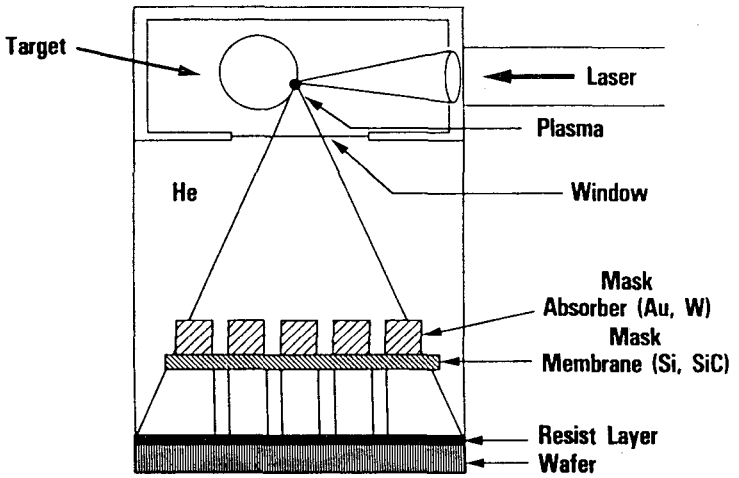
ACCOMPLISHMENTS

- DEEP U.V. IMAGING TECHNOLOGIES INVESTIGATED
- IMAGING SUBSYSTEM CONCEPT DESIGN COMPLETE
- SYSTEM CONCEPT DESIGN COMPLETE
- CHARACTERIZATION OF TEST MASK UNDERWAY

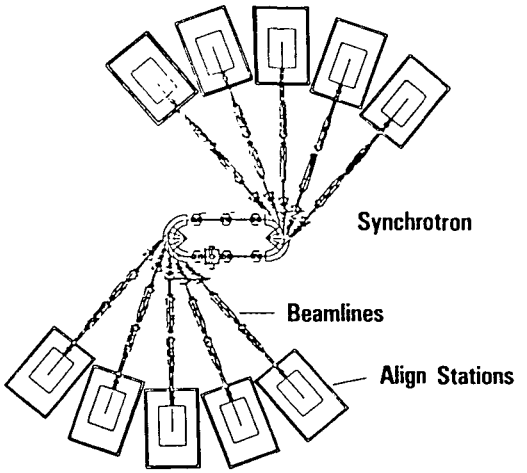
XRL-85

X-RAY LITHOGRAPHY

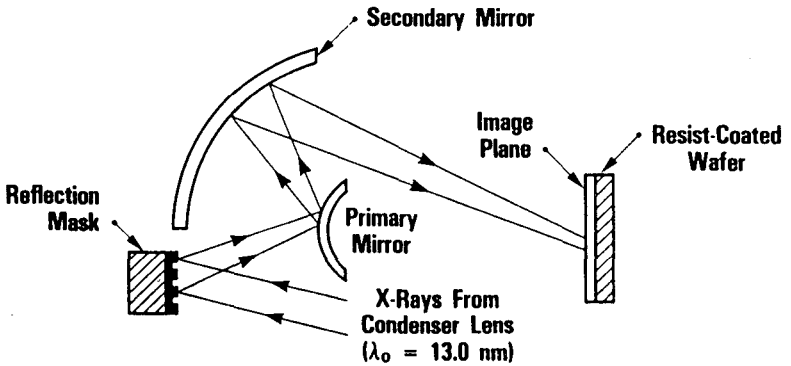
Proximity (Plasma Source)



Proximity (Synchrotron)



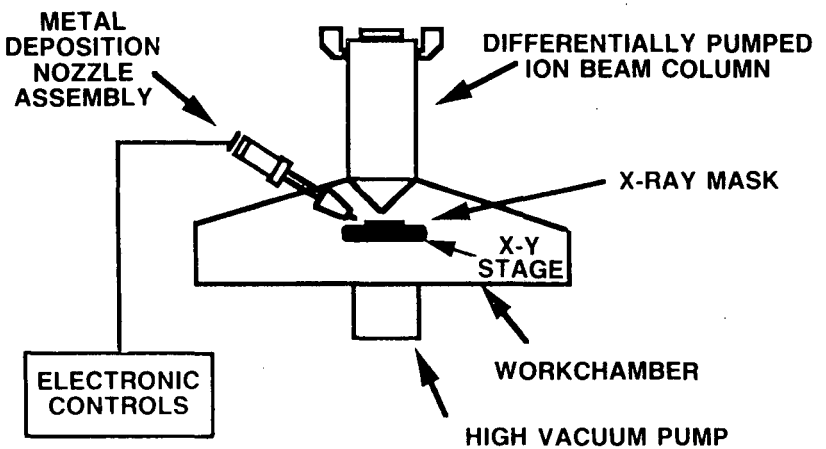
Projection



LITH-117
1801-6-14-90-4

MICRION CORPORATION
X-RAY MASK REPAIR SYSTEM

MASK REPAIR USING FIB FOCUSED ION BEAM



PROJECT GOALS

- DEVELOP REPAIR PROCESSES
- 0.5 μm FEATURE REPAIR BY 3/91
- 0.25 μm FEATURE REPAIR BY 9/92
- COMPATIBLE WITH KLA INSPECTION SYSTEM

APPROACH

- USE EXISTING TOOL (808) AS STARTING POINT
- MODIFY HARDWARE FOR HIGHER RESOLUTION
- DEVELOP FIB SPUTTERING FOR REMOVAL
- DEVELOP METAL DEPOSITION FOR FILL

ACCOMPLISHMENTS

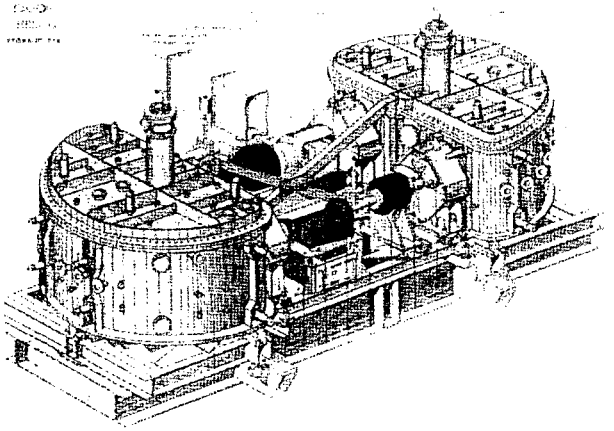
- HIGH RESOLUTION COLUMN INSTALLED
- ADVANCED COLUMN DEVELOPMENT INITIATED
- TUNGSTEN AND GOLD DEPOSITION INSTALLED
- VERIFIED GOOD CONTRAST FOR TUNGSTEN DEPOSITION

XRL-83

1271 8 2 90 18

IBM XRL MASKS AND INTEGRATION

X-RAY LITHOGRAPHIC TECHNOLOGY



PROJECT GOALS

- DELIVER 0.5-μm MASKS (PHASE 1)
- DELIVER 0.35-μm, 0.25-μm MASKS (PHASE 2, 3)
- TRANSFER/LICENSE MASK PROCESS (PHASE 2)
- LEASE/LICENSE E-BEAM TOOL (PHASE 2)
- EVALUATE AND DEMONSTRATE X-RAY LITHOGRAPHY APPLICATIONS

APPROACH

- BUILD ON LARGE-SCALE CORPORATE PROGRAM UNDER WAY
- CONTINUOUSLY ENHANCE MASK PROCESS, ADD INSPECTION/REPAIR
- INSTALL/SUPPORT MASK PROCESS AND E-BEAM TOOLING AT COMMERCIAL MASK CENTER
- RUN PILOT-LINE DEMO LOTS AT IBM

ACCOMPLISHMENTS

- BASE MASK PROCESS RUNNING
- EASLY MASK SAMPLES DELIVERED
- E-BEAM LEASE CONCEPT PLAN DELIVERED
- PILOT-LINE TEST SITE DESIGN RELEASED FOR X-RAY MASK BUILD
- CHARACTERIZED >20 TYPES OF MASK DEFECTS

XRL-82

1801 7 19 90 3

SOURCE/ALIGNERS/RESIST - CONTRACTORS

X-RAY LITHOGRAPHY

CONTRACTORS	TASKS
HAMPSHIRE INSTRUMENTS	LASER PLASMA SOURCE/ALIGNER
PERKIN ELMER	ALIGNER FOR SYNCROTRON TO BE DELIVERED TO UNIVERSITY OF WISCONSIN
	STEPPER (ROTATING ANODE SOURCE)
ROHM & HAAS	HIGH SENSITIVITY RESISTS
BROOKHAVEN NATIONAL LABORATORY	COMPACT SYNCHROTRON DESIGN
GRUMMAN	INDUSTRIAL SUPPLIER OF SYNCHROTRON
GENERAL DYNAMICS	INDUSTRIAL SUPPLIER OF S/C MAGNETS
UNIVERSITY OF WISCONSIN	SYNCROTRON AVAILABLE FOR INDUSTRY, SEMATECH/SRC CENTER-OF-EXCELLENCE FOR XRL
LAWRENCE LIVERMORE NATIONAL LABORATORY	UPGRADE LASER POWER FOR LASER PLASMA SOURCE

XRL-74

MASK - CONTRACTORS

X-RAY LITHOGRAPHY

CONTRACTORS	TASKS
PERKIN ELMER	MASK WRITING, MASK SUPPLIER
HAMPSHIRE INSTRUMENTS	LASER PLASMA SOURCE/ALIGNER
STANFORD UNIVERSITY	E-BEAM TECHNOLOGY, 0.25 MICRON PATTERNS
MIT	TUNGSTEN FILMS
KLA	AUTO INSPECTION OF MASK DEFECTS
MICRION CORPORATION	MASK REPAIR
IBM	MASK TECHNOLOGY DEVELOPMENT
HORIZON TECHNOLOGY	
NANOSTRUCTURES	Si, SiC MEMBRANES
CRYSTALLUME	DIAMOND MEMBRANES
LEPTON	DEMONSTRATING NEW EB EQUIPMENT

DEVICE DEMONSTRATIONS - CONTRACTORS

X- RAY LITHOGRAPHY

IBM	CMOS FABRICATION - MIX & MATCH WITH OPTICAL STEPPER - 3 SOURCE-TYPES OF X-RAY EXPOSURE
HONEYWELL	CMOS FABRICATION - 0.5 MICRON GATE POLY LAYER - MIX AND MATCH SYSTEM - POINT SOURCE X-RAY EXPOSURE
SANDERS	GA AS DEVICES FOR MICROWAVE APPLICATION - TRANSISTORS - ANALOG ICS

XRL-72

ACCOMPLISHMENTS - FY90
X-RAY LITHOGRAPHY

MASK TECHNOLOGY ($9M)

- Micrion demonstrated good contrast with tungsten deposition on "clear" defects
- IBM masks distributed to other contractors in the X-Ray Lithography program
- Crystallume delivered diamond substrates, 30 mm diameter, under tension
- Set interim mask standard (Key roles by NIST, IBM, U of Wisconsin, SVG)
- NRL fabricated laminate membranes, selectively deposited tungsten at < 150°C
- Stanford U. deposited tungsten into oxide grooves for masks (0.15 microns resolution)

SOURCES ($11M)

- Hampshire Instruments delivered first laser plasma source (to AT&T)
- Brookhaven's Phase 1 (warm magnet) machine placed under test
- University of Wisconsin completed beam line designs (field of 2.5 cm X 5.0 cm)

ALIGNERS/RESISTS ($5M)

- SVG passed the critical design review for mask-to-wafer aligner for the synchrotron
- Both Hampshire Instruments and SVG aligners demonstrated overlay of 0.1 microns
- Rohm & Haas made samples of negative resist (<10 mJ/sq cm) widely available

PROCESS INTEGRATION ($5M)

- Honeywell completed first lot of CMOS test circuits using SVG x-ray stepper
- U. of Wisconsin installed diagnostic equipment in new clean room (area = 185 sq m)
- U. of Wisconsin demonstrated 0.06 micron linewidth using synchrotron exposure

XRL-122

XRL OPPORTUNITIES FOR OTHER AGENCIES

DoE

- X-RAY SOURCES
  SYNCHROTRON
  PLASMA SOURCES
  RF WIGGLER - FEL - TRANSITION

- X-RAY OPTICS
  REDUCTION
  COLLIMATION

- RESISTLESS PROCESSING

DoC

- METROLOGY - STANDARDS

NSF

- UNIVERSITY PROGRAMS IN SOURCES, MATERIALS, BEAM-MATTER INTERACTIONS

XRL-66

ISSUES

FUNDING ? ? ?

XRL-56

808-4-21-89-2

UNIQUENESS OF THE ADVANCED LIGHT SOURCE

David Attwood

Center for X-ray Optics
Lawrence Berkeley Laboratory

Berkeley Strengths for the Pursuit of New Programs in X-ray Lithography

- The ALS — spectrally peaked for soft x-rays, LBL's new flagship
- UC Berkeley — Faculty expertise in optical lithography. Quality graduate students
- CXRO — expertise in soft x-ray techniques

Science Times

Quest for Fastest Computer Chip: International Contest Intensifies

With Japan surging, U.S. reaches for X-rays that promise vast increase in power.

By WILLIAM J. BROAD

THE race for dominance in making semiconductors, the tiny chips that carry electronic circuits, is entering a new phase as scientists convinced they have almost exhausted the present technology strive to use X-rays to make chips that are faster and more powerful.

In the mid 1990's, the winners of this contest are expected to rule the most advanced part of the $100 billion annual chip market and to propel chip-related industries such as computer manufacturing to new heights. The losers can expect an erosion of their industrial might and military strength, which are intimately tied to high-technology systems.

Keenly aware of the stakes, the Federal Government earmarked $25 million in the current budget to perfect the X-ray technology. But that is only a small fraction of what experts in the United States believe the Japanese and even the Europeans are spending.

The goal of X-ray lithography, as the technique is known, is to use giant particle accelerators known as synchrotrons to etch finer semiconductor circuits than ever before.

If perfected, the process would cram far more components onto the fingernail-sized chips that drive most electronic devices, including computers. While the best chips today bristle with a million or so circuits, future ones created with X-rays conceivably might hold up to a billion.

Such densities promise vast increases in chip power and speed, since it takes less time for electrical signals to zip among closely packed components. To date, most chip advances have come from shrinking the distance between circuits.

The contest has a sense of urgency because coventional methods are being pushed to the limit, because foreign competition is rising and because the technology itself has proven to be reliable after a decade of preliminary research.

Synchotrons are close cousins of giant atom smashers and produce X-rays obtainable in no other way.

Charles H. Ferguson, a former analyst for the International Business Machines Corporation who is now at the Massachusetts Institute of Technology's Center for Technology, Policy and Industrial Development, said: "Synchrotrons look like an extraordinarily powerful technology, but they will be very expensive to develop and operate. The projected capital cost of a synchrotron chip factory is $500 million."

Indeed, the X-ray goal is so ambitious and costly that no single corporation has the resources to achieve it.

"It's a very exciting period because of the Federal

Continued on Page 19

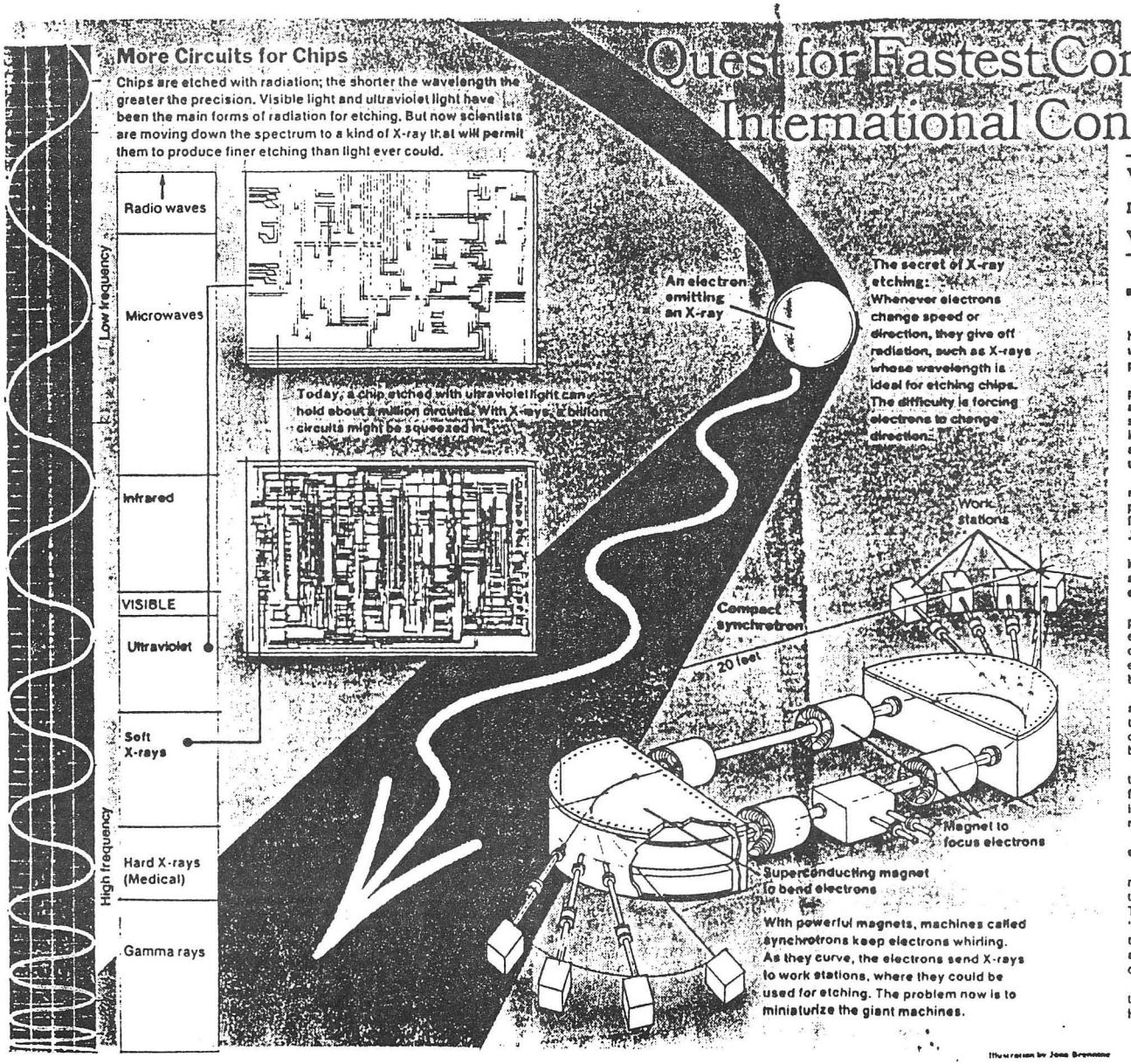
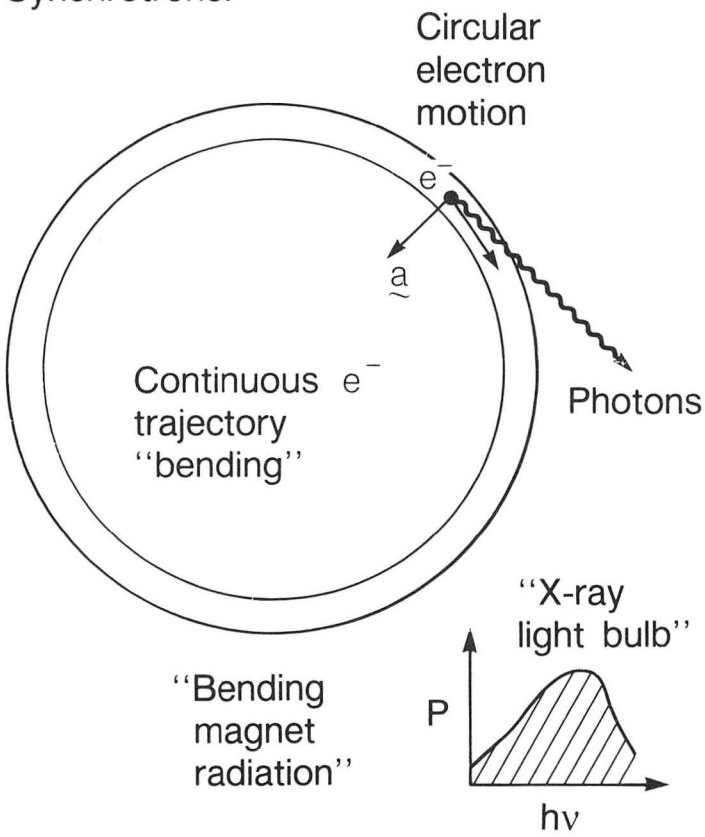


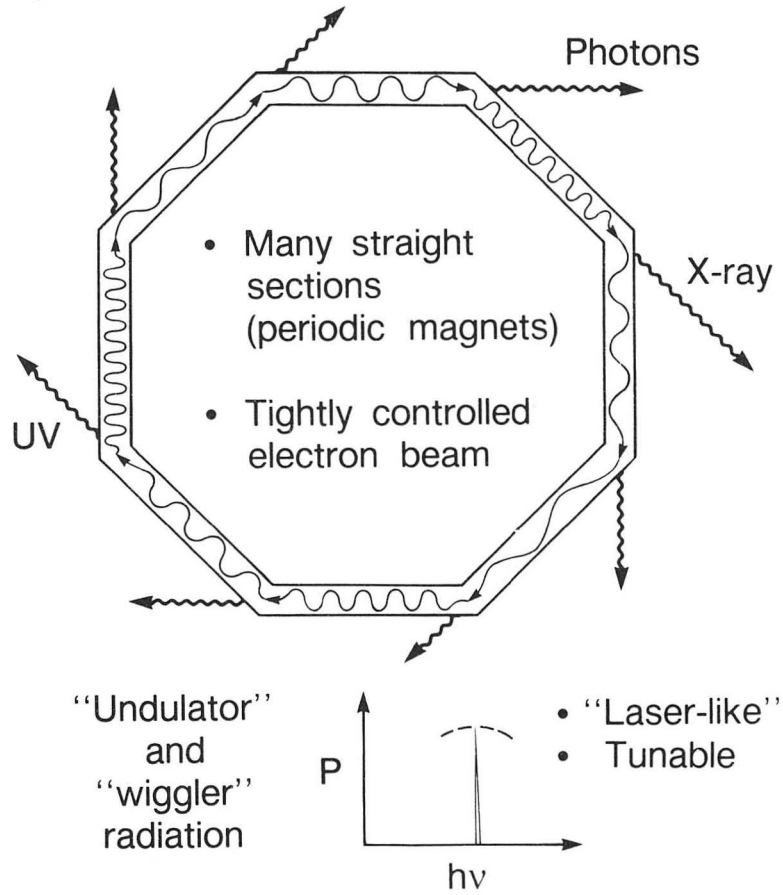
Illustration by Jane Brownlow

Evolution of Synchrotron Radiation

Todays Synchrotrons:



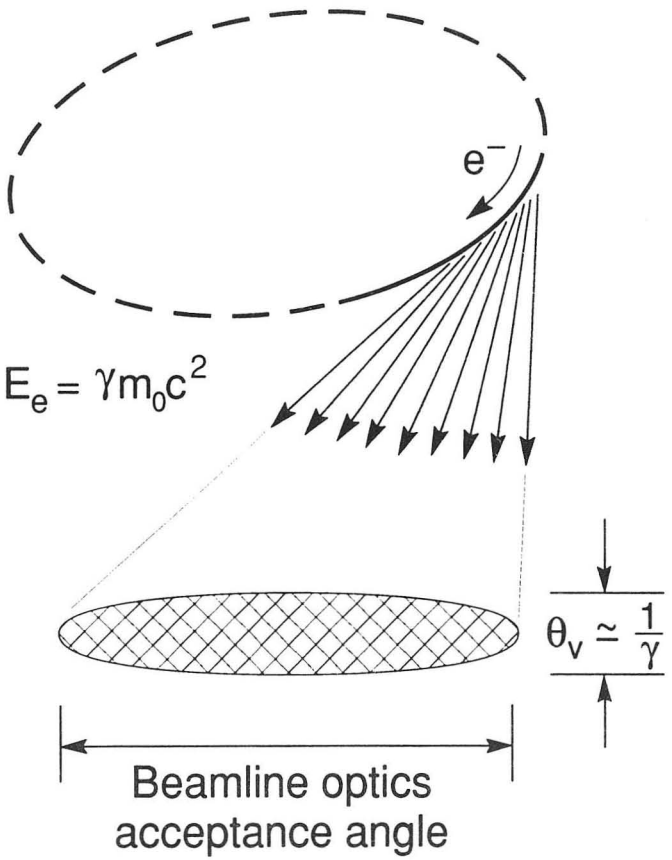
Tomorrows Synchrotrons:



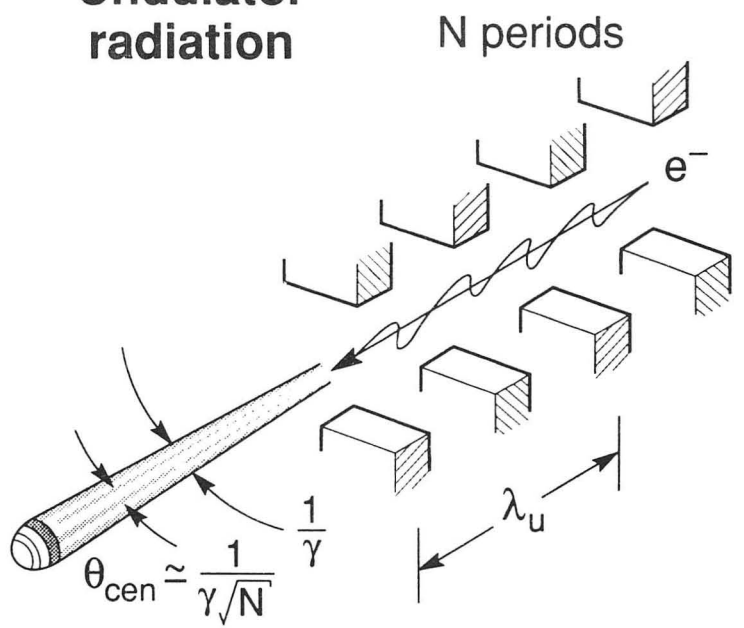
XBL 888-8937

The ALS Has Both Undulators and Bending Magnets

Bending magnet radiation (sweeping searchlight)



Undulator radiation



$$\lambda_x = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

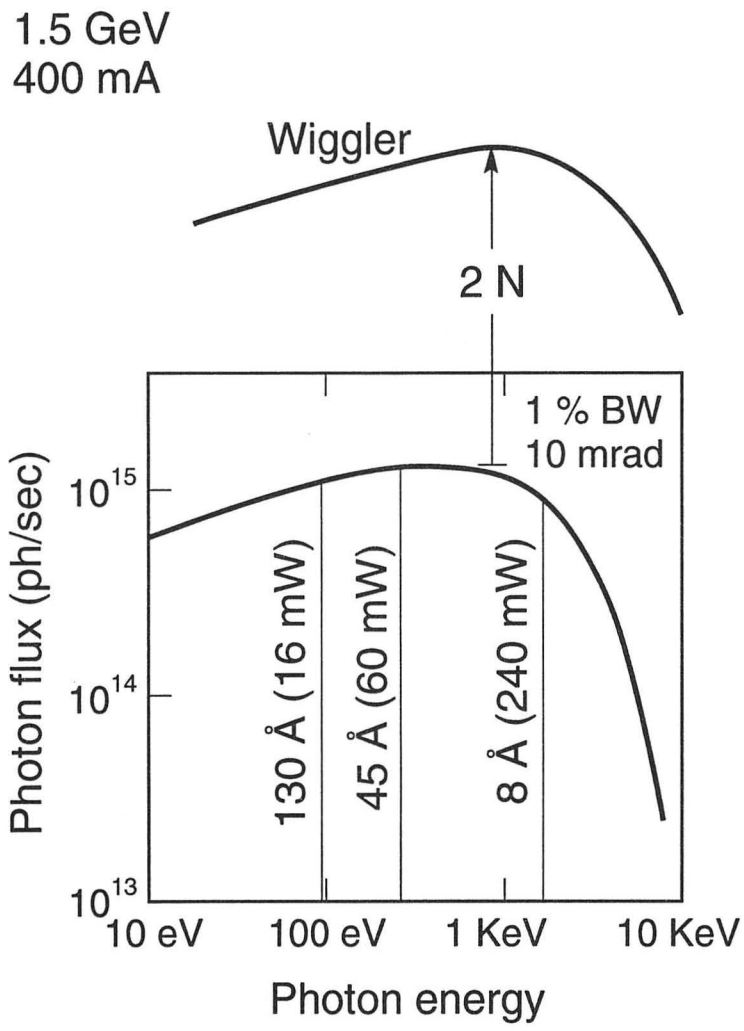
in the central radiation cone:

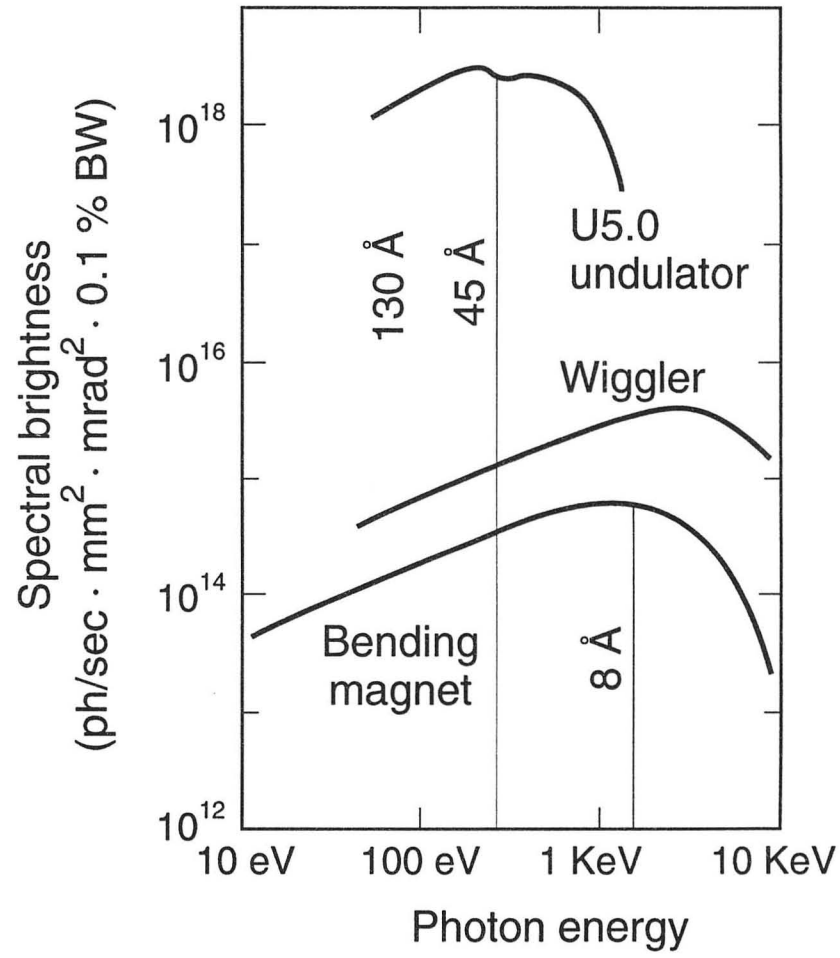
$$\frac{\Delta\omega}{\omega} \simeq \frac{1}{N}$$

$$\theta_{cen} \simeq \frac{1}{\gamma\sqrt{N}}$$

XBL 911-6408

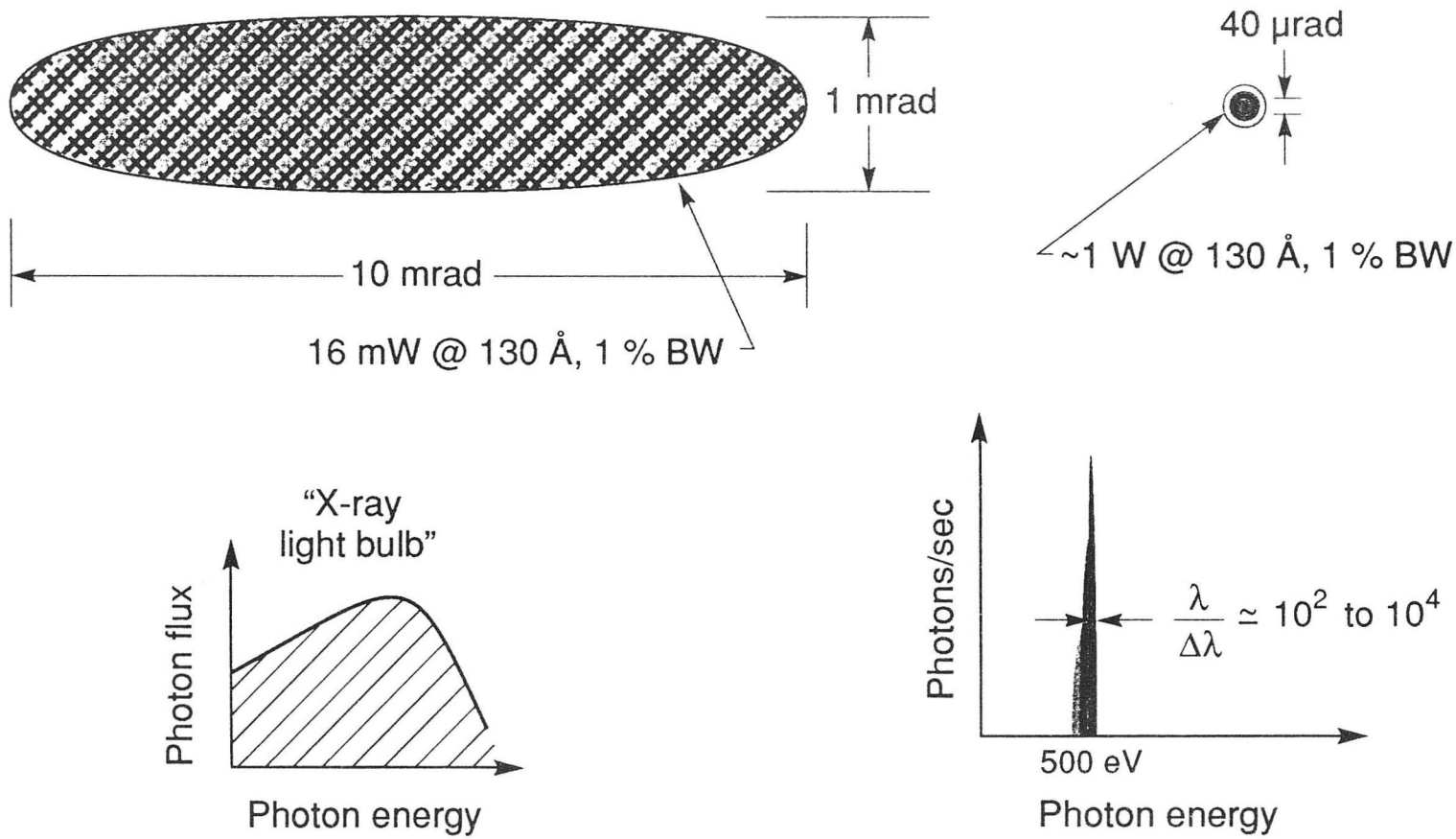
The ALS Spectrum is Ideal for X-ray Lithography





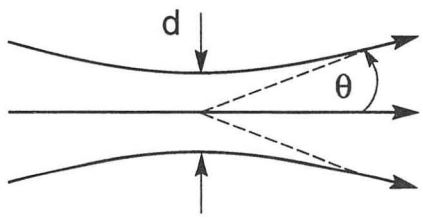
XBL 911-6409A

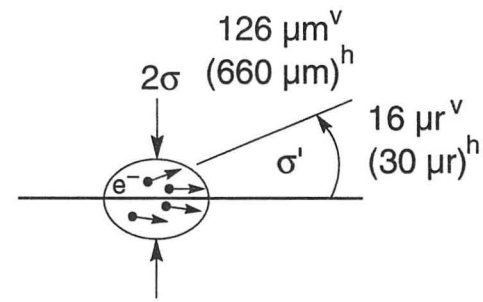
Angular Divergence of Bending Magnet and Undulator Radiation



Coherence Properties of Undulator Radiation

Spatial Coherence





Photon phase-space volume* $= d \cdot \theta = \frac{\lambda}{2\pi}$

$2\sigma \cdot \sigma' = e^-$-beam phase-space volume*

$$\frac{\lambda}{2\pi} = 2\sigma \cdot \sigma'$$

$$\boxed{\lambda = 4(\pi\sigma\sigma')}$$

For the elliptical ALS electron beam:

120 Å vert. plane (≃ diffr. ltd @ 130 Å)
1200 Å horiz. plane (≃ 10 x diffr. ltd @ 130 Å)

Temporal Coherence

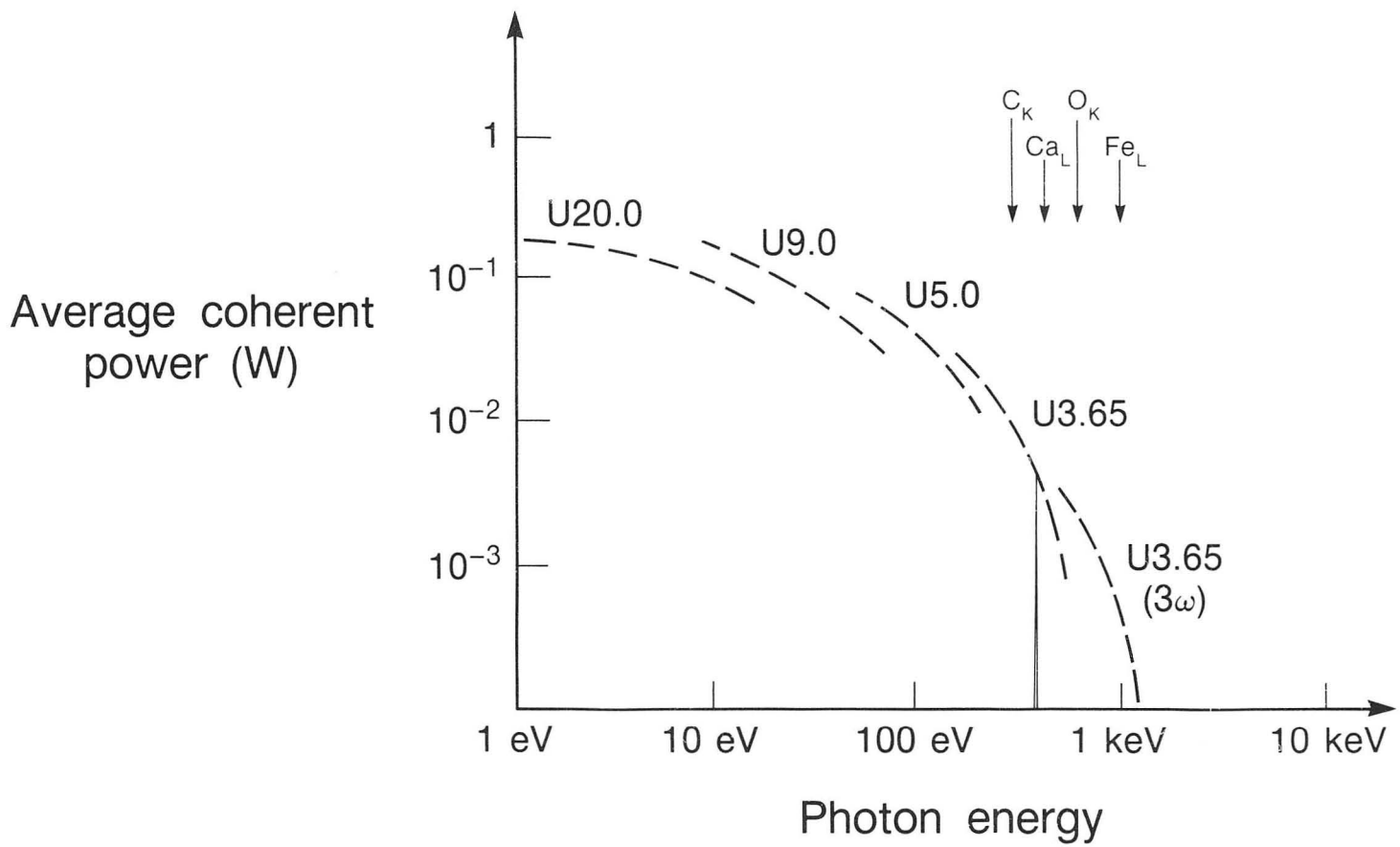
$$\boxed{\ell_{coh} = \frac{\lambda^2}{\Delta\lambda} = \left(\frac{\lambda}{\Delta\lambda}\right)\lambda}$$

$(10^2)(130\ \text{Å}) \simeq 1.3\ \mu\text{m}$

*Assumes Gaussian beam, rms quantities.
Undulator condition is $\sigma' < \frac{1}{\gamma\sqrt{N}}$.

XBL 911-6412A

Coherent Radiation at X-Ray and VUV Wavelengths



XBL 874-9024

Bending Magnet Radiation and Beamlines

Advantages

- Covers a smooth, broad spectrum without magnet tuning
- Output power is relatively high
- Large angular divergence reduces thermal loading on optics
- Beamlines are less expensive (no undulator magnet structure, no water-cooled optics)

Disadvantages

- Spectral brightness is orders of magnitude less than undulator radiation

Undulator Radiation and Beamlines

Advantages

- Very high brightness and partial coherence
- Output power relatively high, narrow bandwidth and relatively low divergence
- Excellent for use in focussed microscopy and high resolution spectroscopies in the physical and life sciences

Disadvantages

- High thermal loading makes the beam lines expensive
- Spectral tuning is possible, but not as broad or convenient as with bending magnet radiation.

Projects That Might Benefit X-ray Lithography Using a Bending Magnet Beamline at the ALS

- Development of a soft x-ray "metrology beamline", relevant to x-ray lithography

- A relatively inexpensive facility for resist, mask, and other project research and development; readily available to university and industrial members of an appropriate consortium

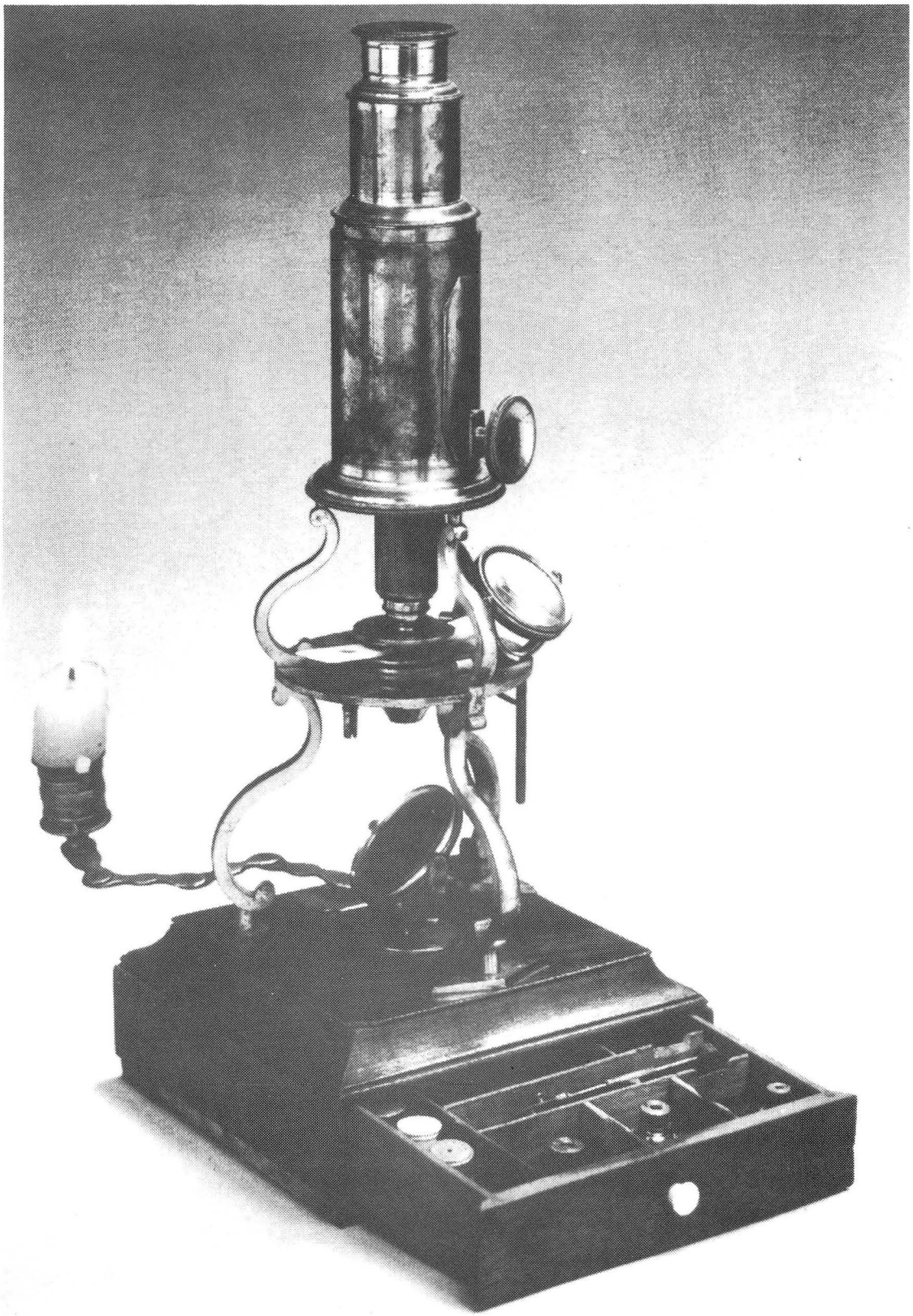
- A lithography test stand for optical systems research over a broad spectral range

Undulator Beamline Projects Relevant to the Development of X-ray Lithography

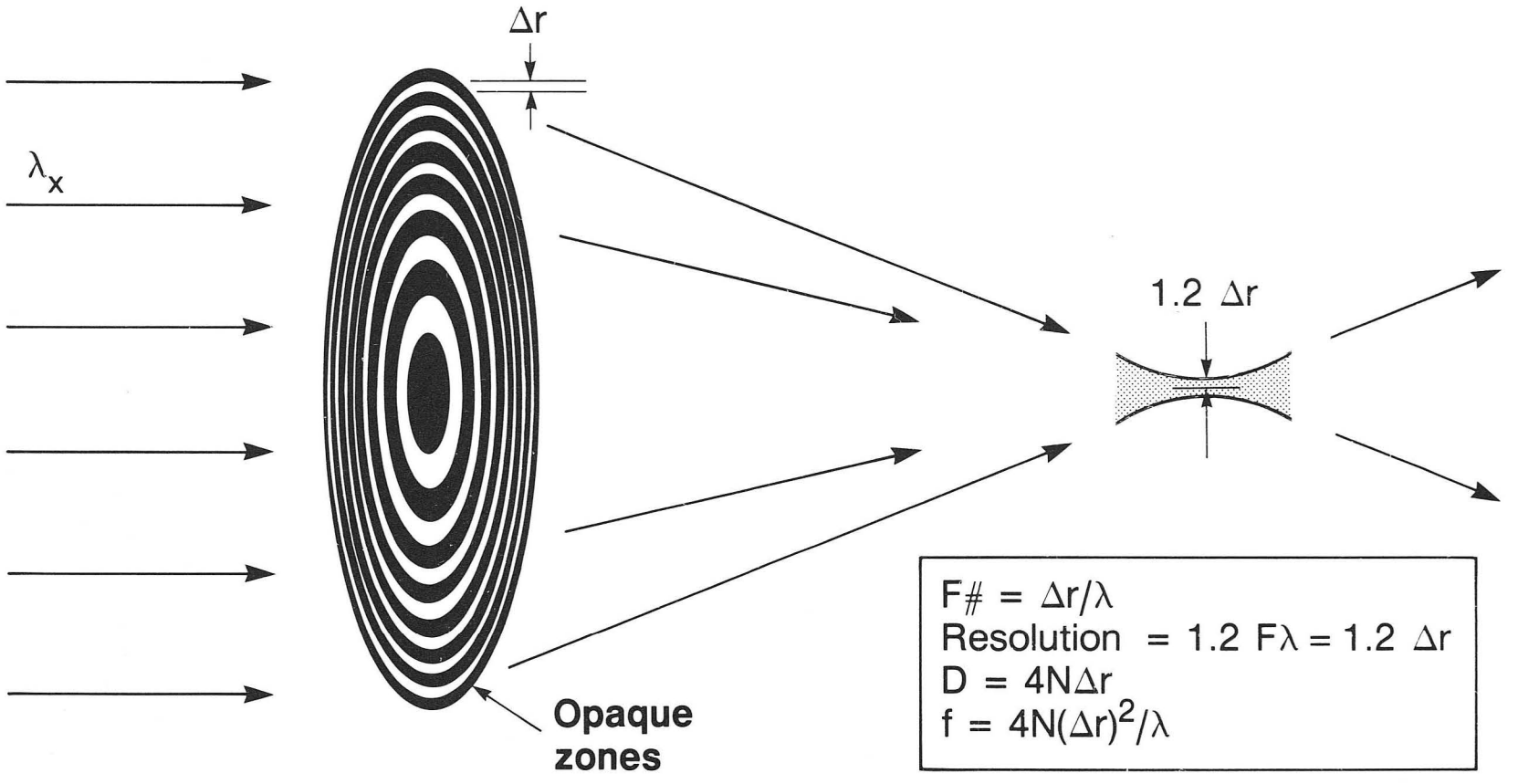
- State-of-the-art source for high spectral brightness, partially coherent soft x-ray generation in a relatively narrow bandwidth (1-3%), narrow radiation cone (~40 μrad)

- Test facility for advanced soft x-ray imaging systems which benefit from relatively high power (~1 Watt) and partial coherence ($\ell_{coh} \cong 1$ μm and 10 times diffraction limited, for $\lambda = 130$Å and 1% bandwidth)

- Unique analytic tool for spatially resolved elemental studies studies of dilute dopants and impurities using zone plate focusing (400Å spot size) and highly monochromatized ($\lambda/\Delta\lambda \sim 10^4$) undulator radiation: photoelectron and emission spectroscopies.



Fresnel Zone Plate Lens for Diffractive Focusing of X-Rays:

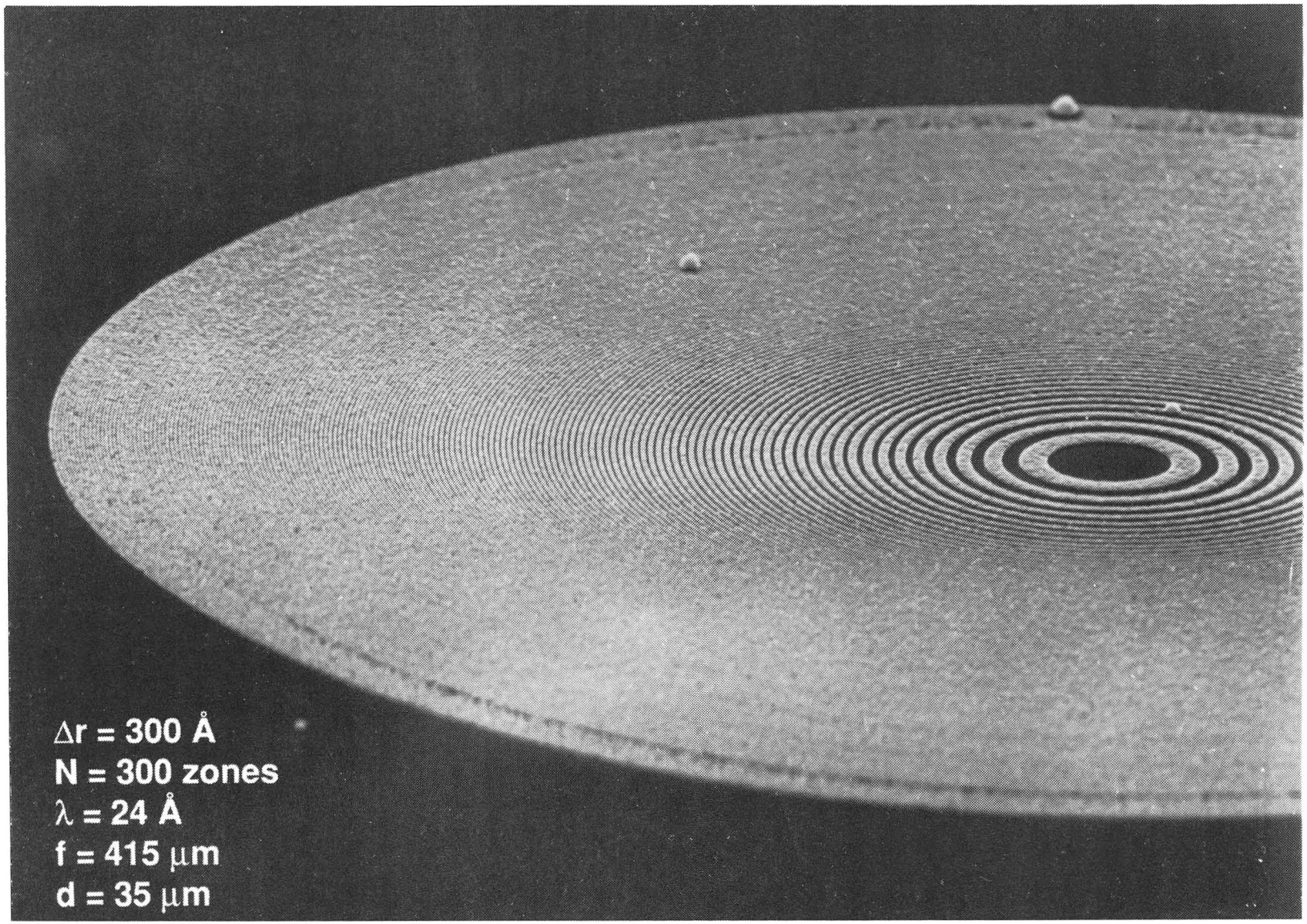


$F\# = \Delta r/\lambda$
Resolution $= 1.2\ F\lambda = 1.2\ \Delta r$
$D = 4N\Delta r$
$f = 4N(\Delta r)^2/\lambda$

XBL 842-9405B

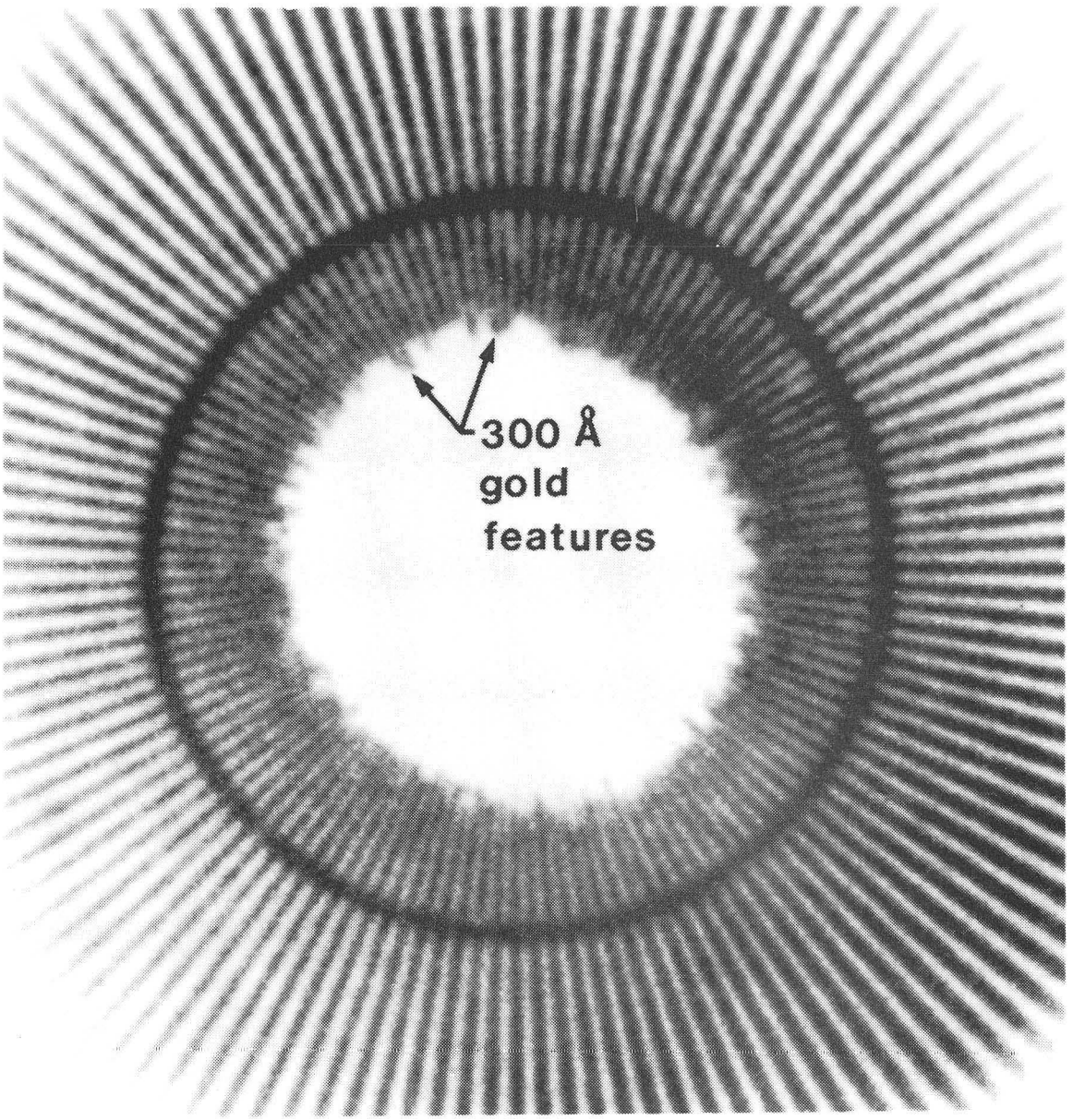
IBM

New 300 Å Gold Zone Plate Lens



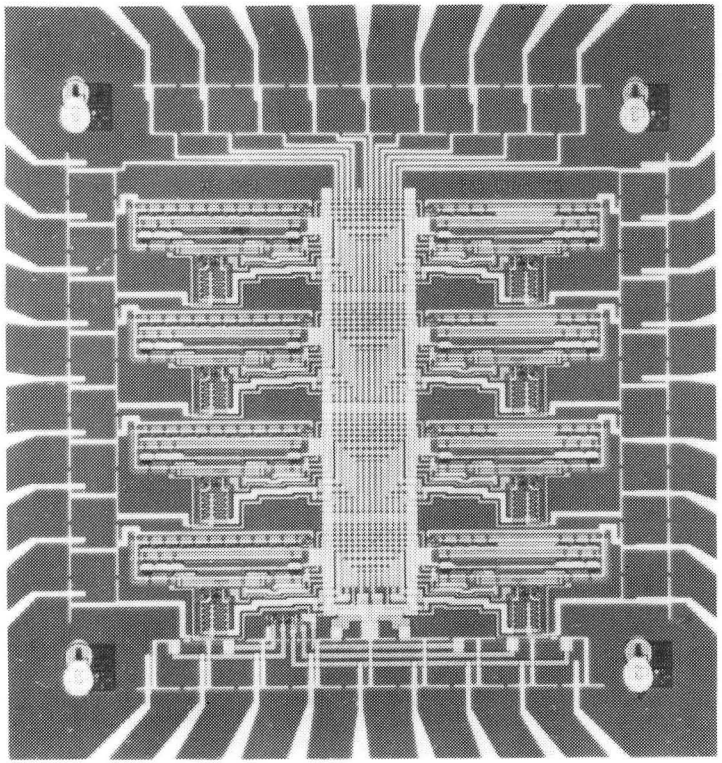
X-ray Image of a Gold Test Pattern Showing 300 Å Features

λ = 24 Å, U. Göttingen x-ray microscope at BESSY

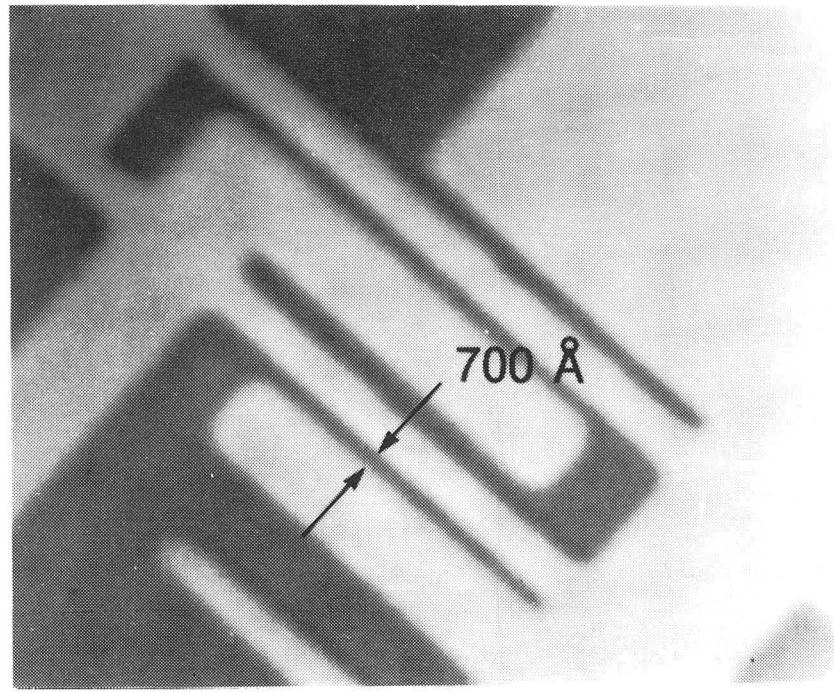


Development of X-ray Microscopy as an Analytic Tool for the Study of Future Deep-submicron Devices and Circuits

Vladimirsky, Kern, Attwood, Meyer-Ilse (LBL, IBM, Göttingen, BESSY)



Optical image

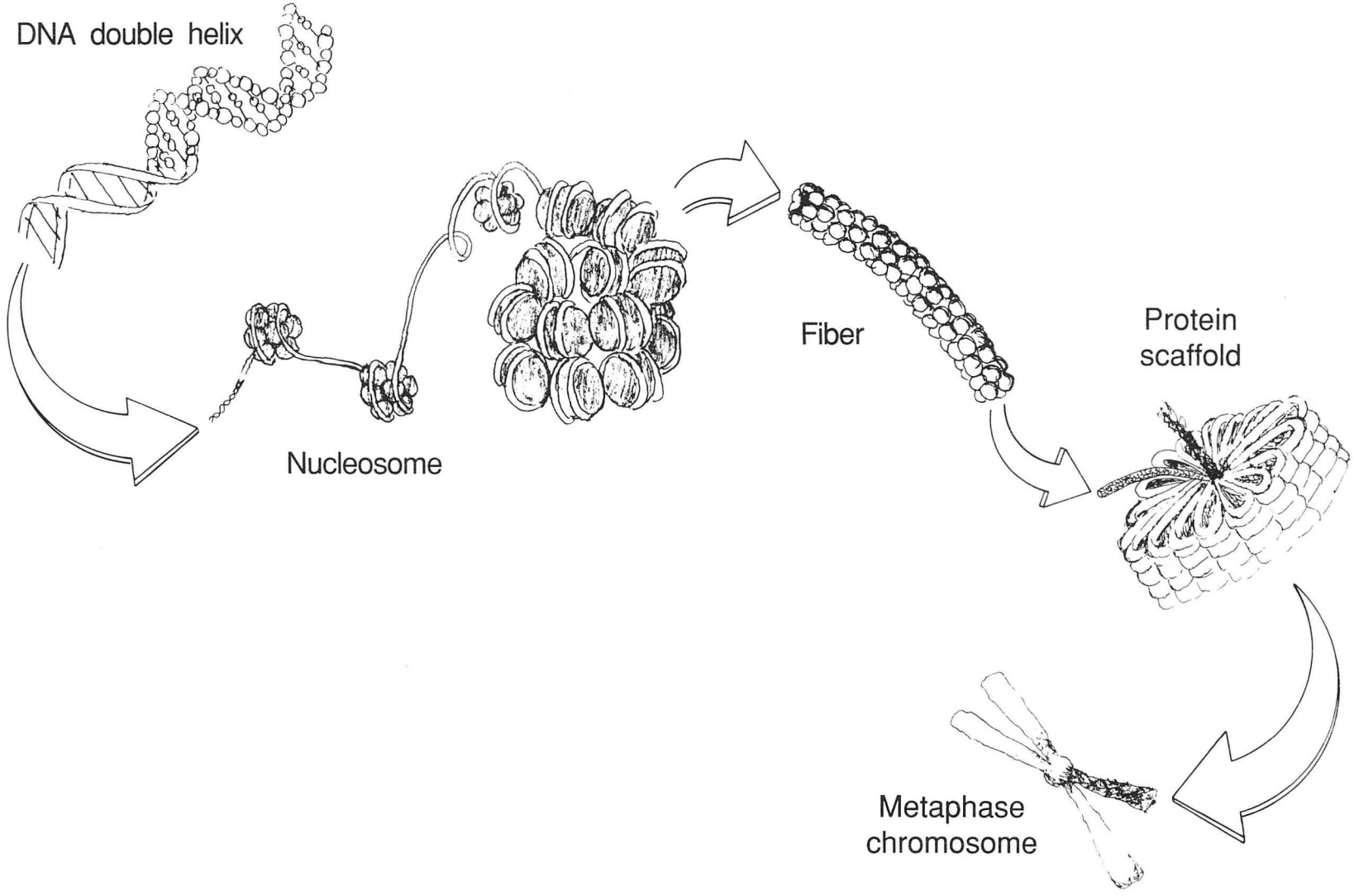


X-ray image of typical pattern detail

Pattern: two levels of an experimental 0.1 micron silicon MOSFET test circuit*

*G. Sai-Halasz et al., IEEE Electr. Dev. Lett., 463 (Oct. 87)

Chromatin Packing: Spatial Features from Ångstroms to Microns

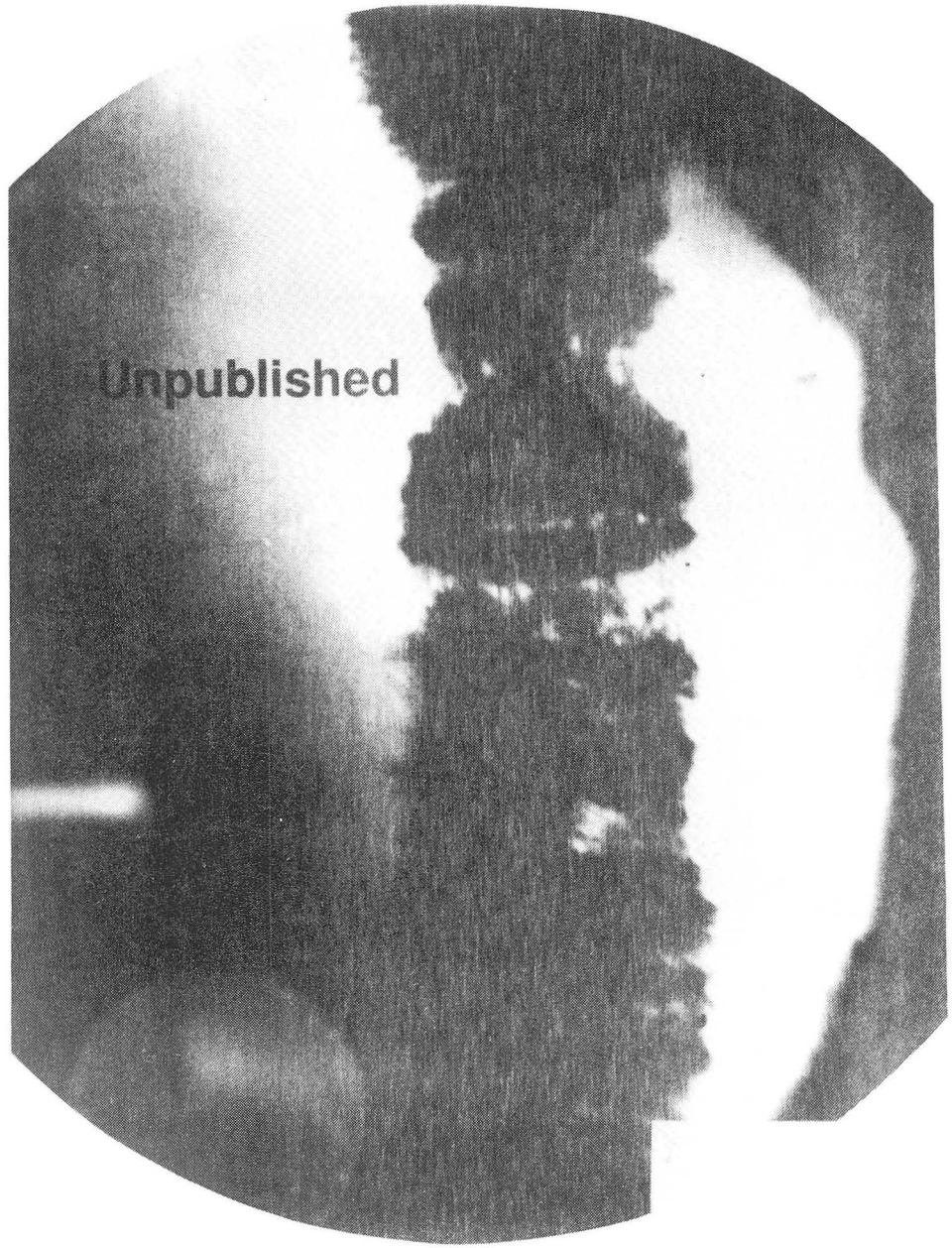


XBL 911-5975

The Göttingen X-ray Microscope at BESSY

X-ray Micrograph Showing Natural Banding and Connective Fibers of the Polytene Chromosome from the Salivary Gland of Chironomous Thummi

G.Schmahl, D.Rudolph et al.,
Instit. Röntgenphysik
Univ. Göttingen
and
Max Planck Institute
für Biophys. & Chemie
Göttingen



4-5 μm diameter
600-700 Å resolution
24 Å wavelength
BESSY Synchrotron, Berlin

The Scanning X-ray Microscope at Brookhaven

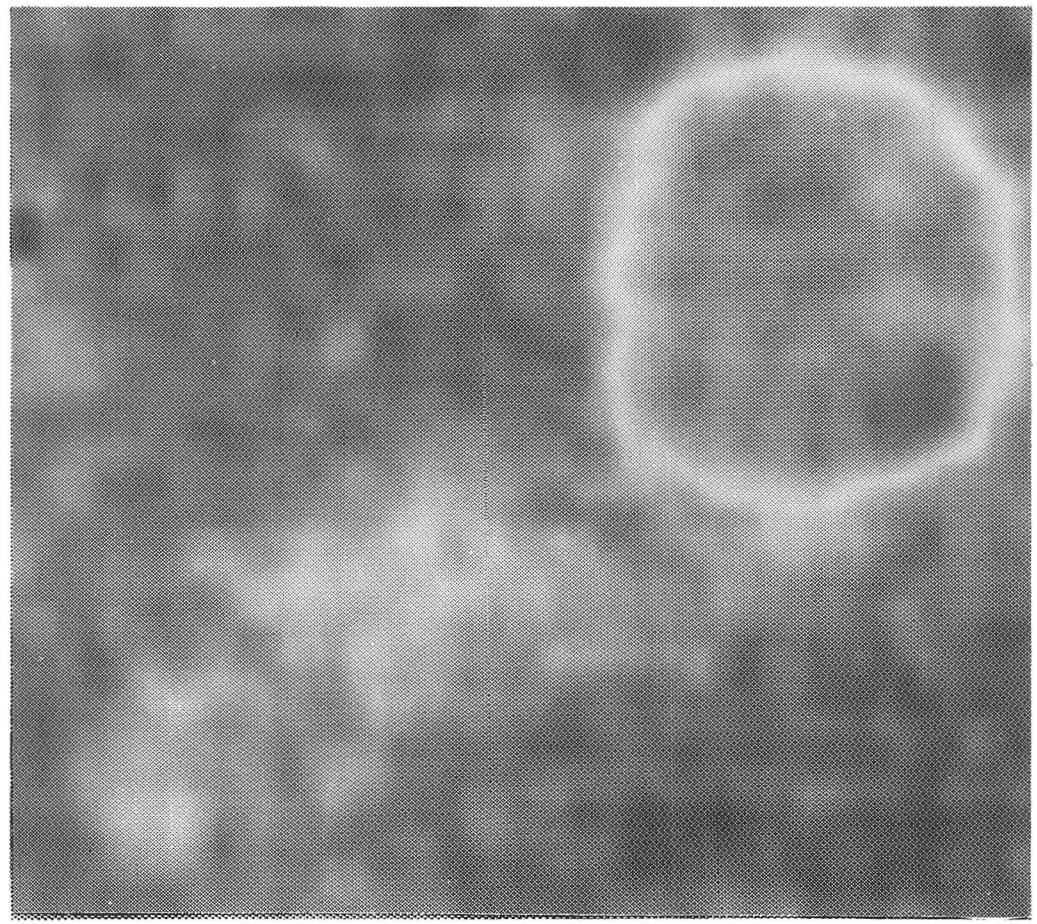
(J.Kirz and colleaques, SUNY Stony Brook)

First View of an Unaltered Subcellular Component

No fixation, no staining, no sectioning, aqueous environment

50 K cps

80 K cps



1,000 Å square

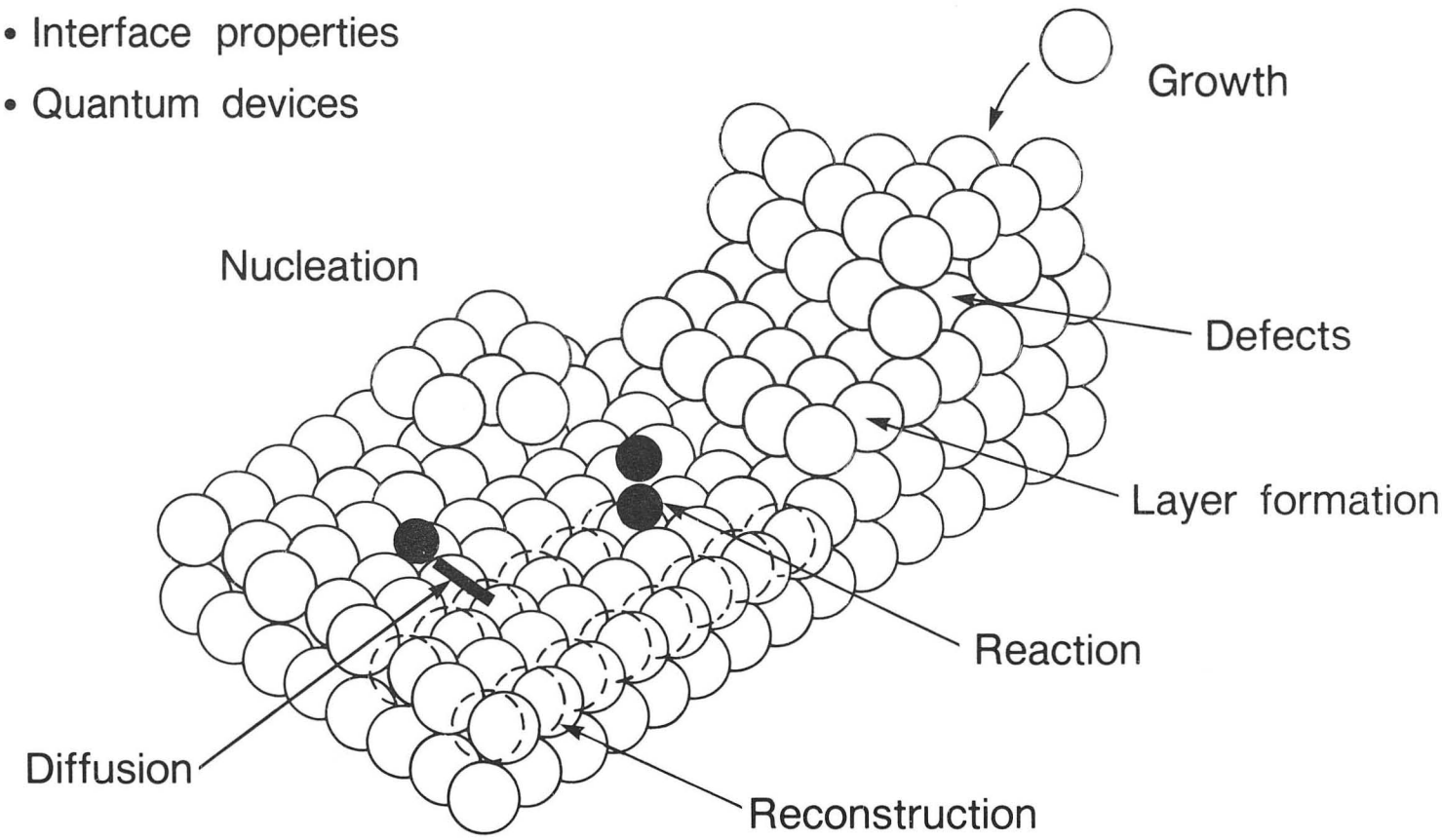
06 FEB 20 CNTM I0 PED MED2×2. INT5

λ = 32Å Radiation dose $\simeq$ 1 megarad

LBL, Stony Brook, NSLS, IBM, UCSF

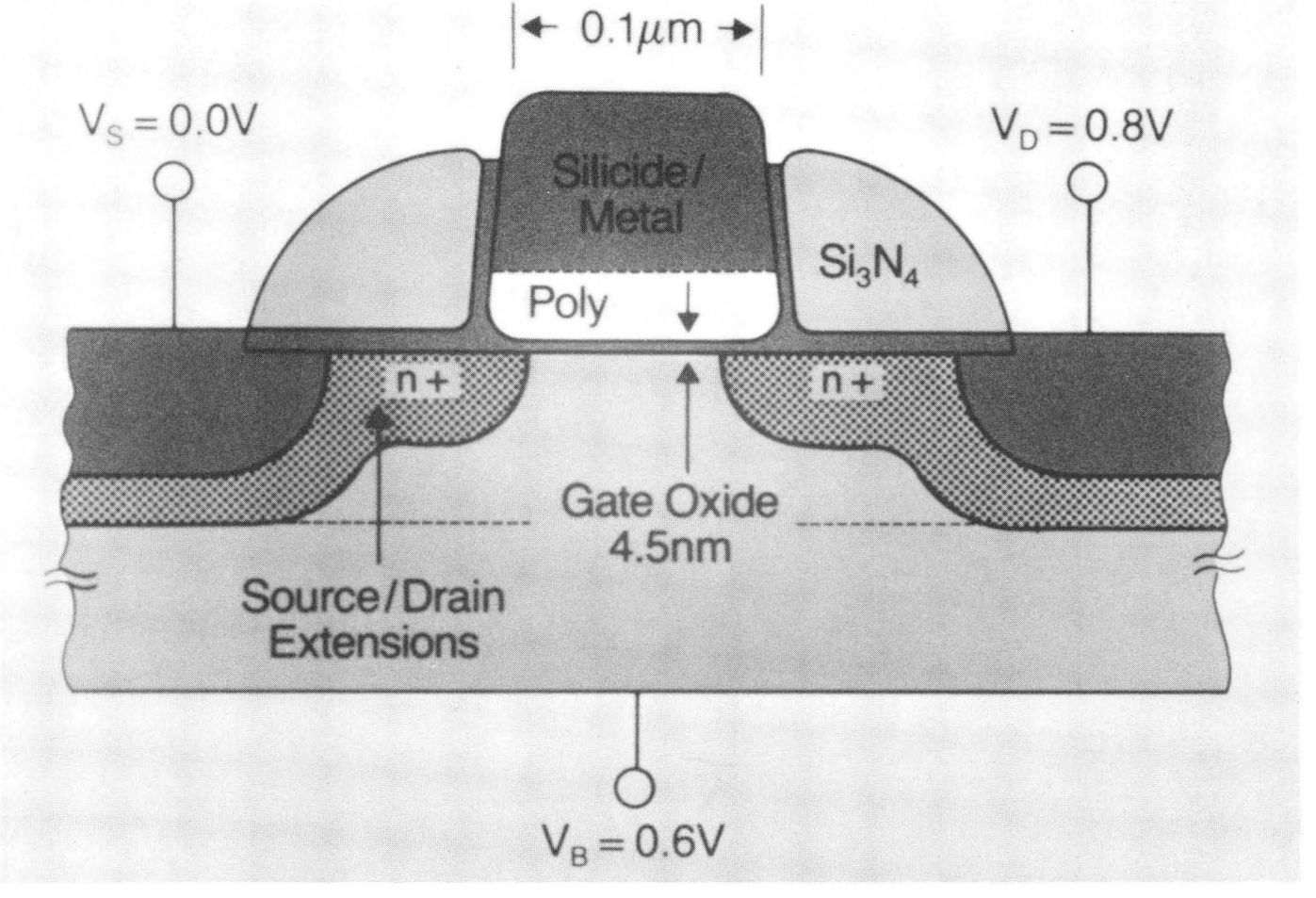
Studies of Surfaces and Thin Films

- Surface chemistry
- Thin film growth
- Interface properties
- Quantum devices



IBM

Ultra Short Channel Si-MOSFETS: 0.1 μm Gate Device

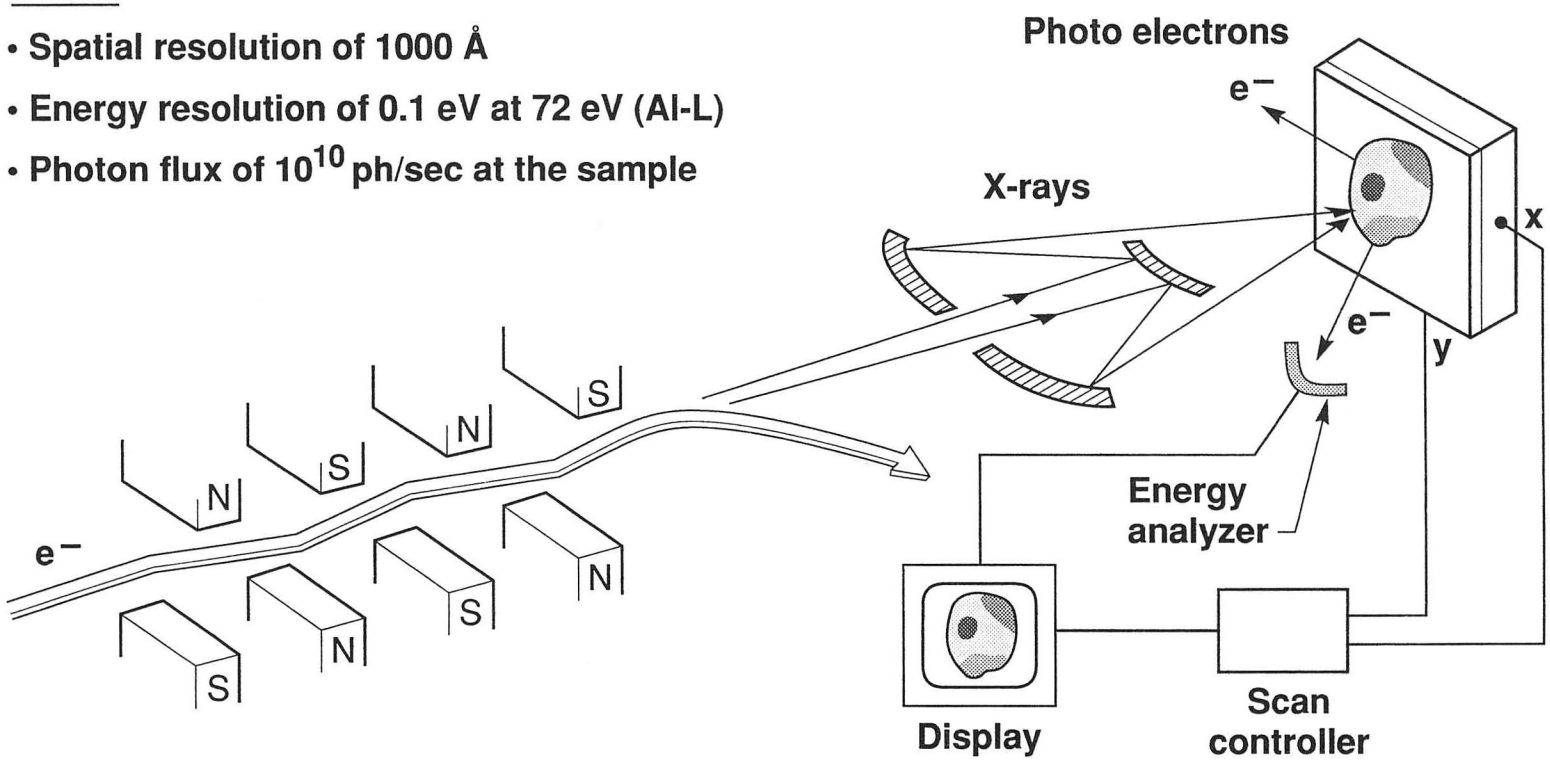


SRC

Chemical Mapping of Semiconductor Surfaces and Interfaces

Goals

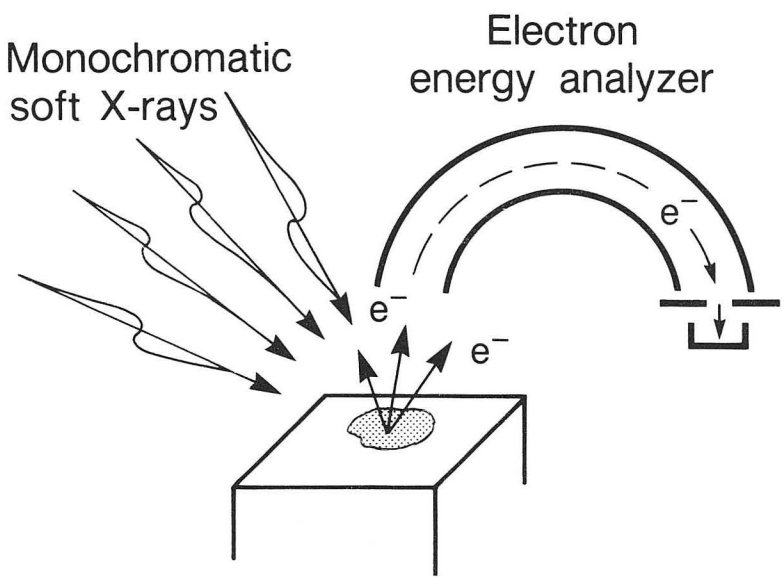
- Spatial resolution of 1000 Å
- Energy resolution of 0.1 eV at 72 eV (Al-L)
- Photon flux of 10^{10} ph/sec at the sample

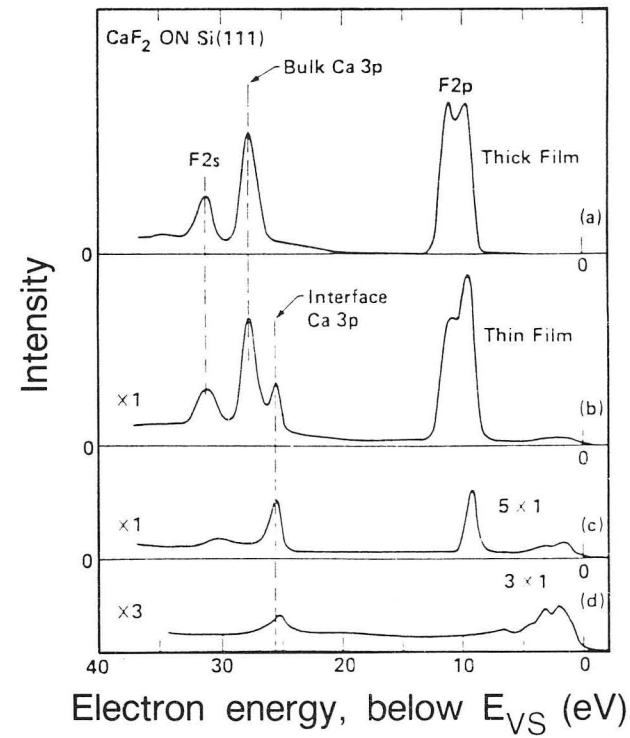


XBL 898-6588C
lg/Mac

Photoelectron Spectroscopy Reveals Electronic Structure of Surfaces and Thin Films

Interface bonding of calcium fluoride on the silicon (111) surface



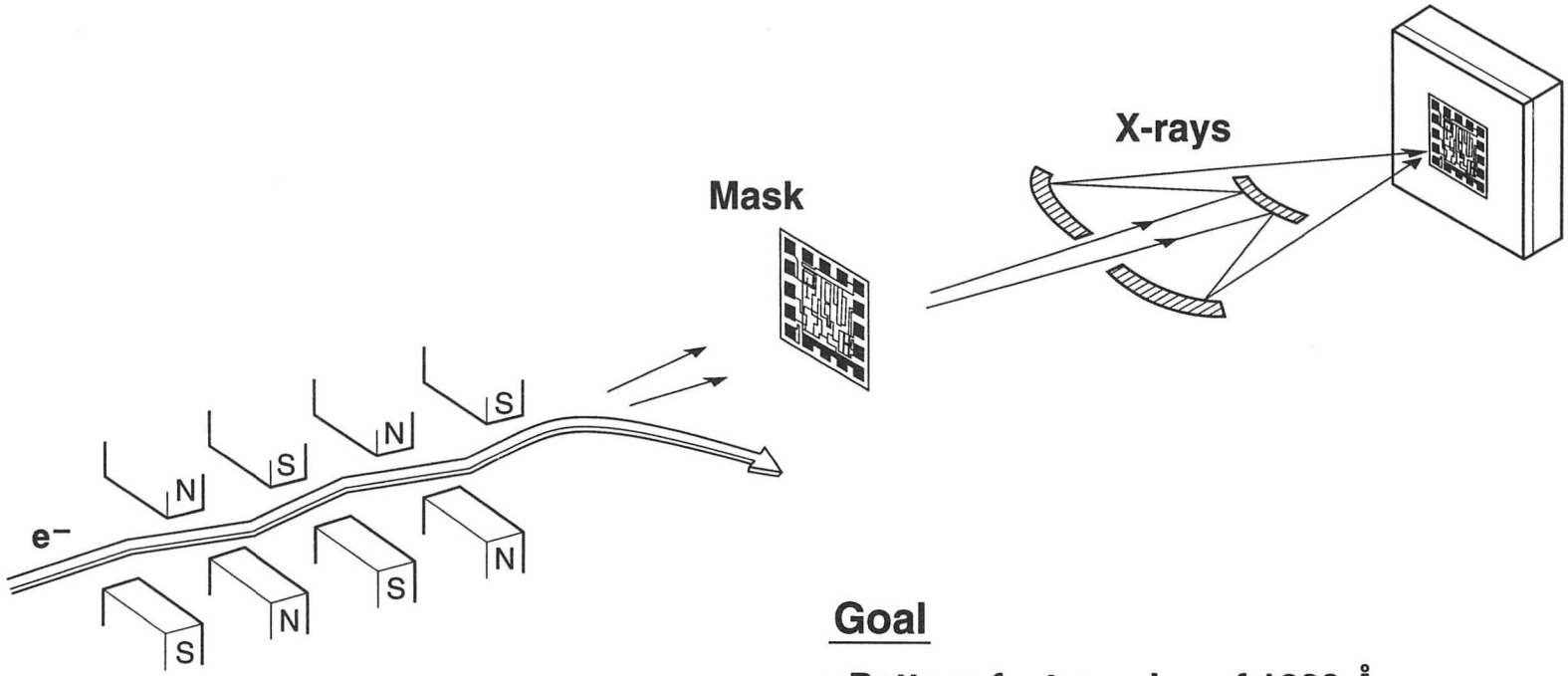


(M. Olmstead et al., Phys. Rev. B, '87)

XBL 882-8844

Reduction X-ray Lithography Using Reflective Optics

(CXRO/LBL and CXRL/U.Wisc.)

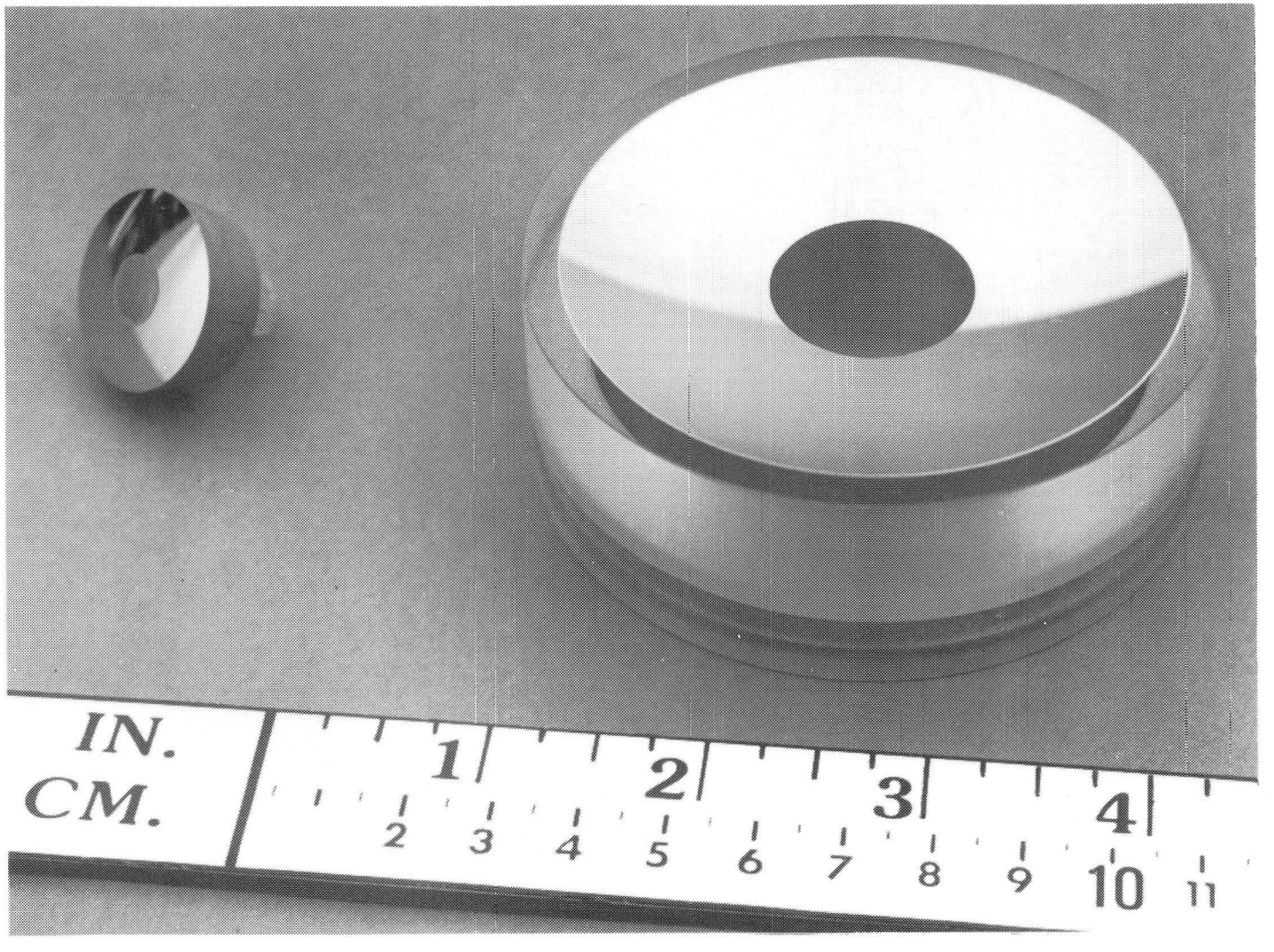


Goal

- Pattern feature size of 1000 Å

XBL 898-6588A

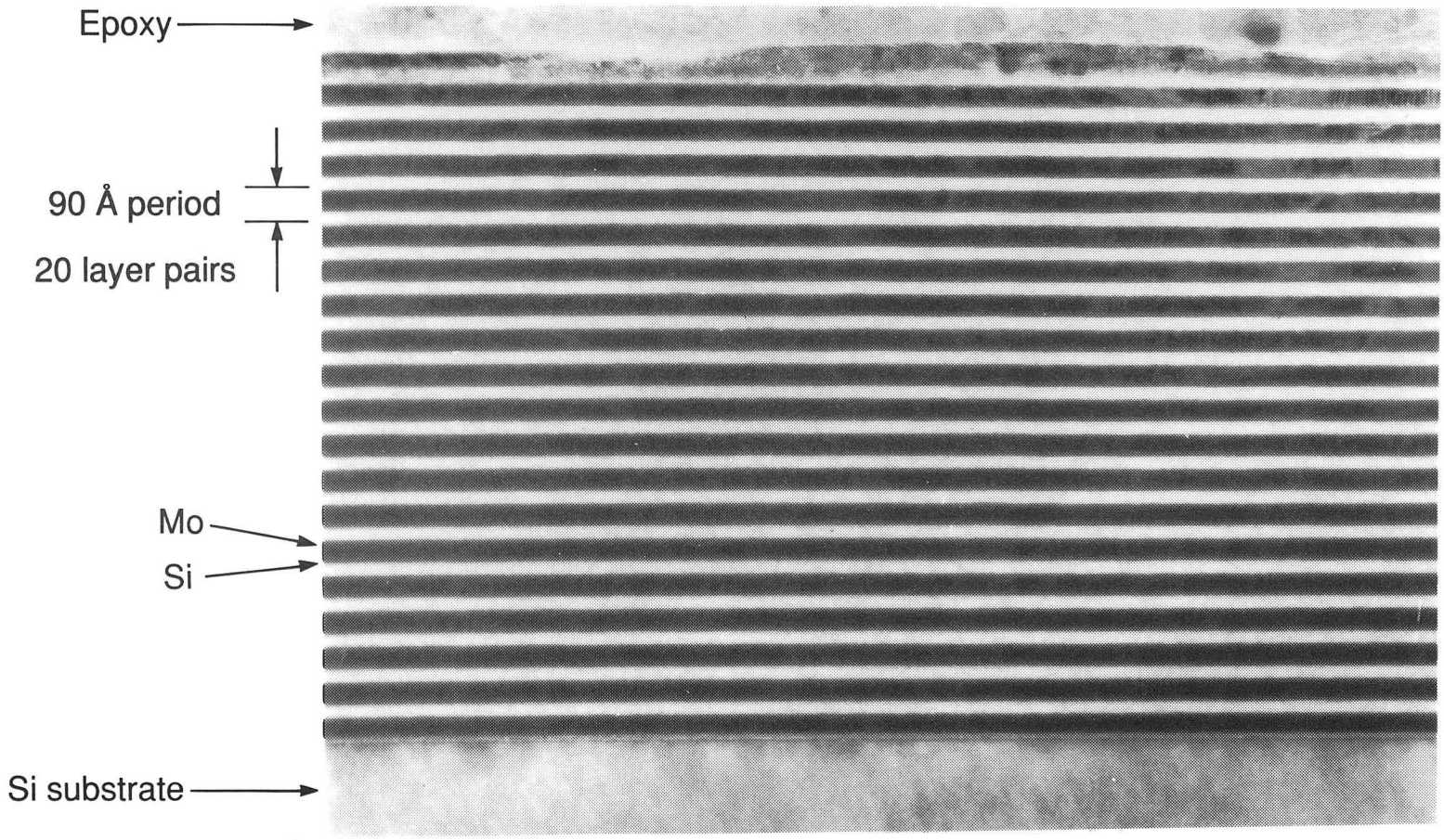
Multilayer Coated Reflective Optics for Photoelectron Microscopy



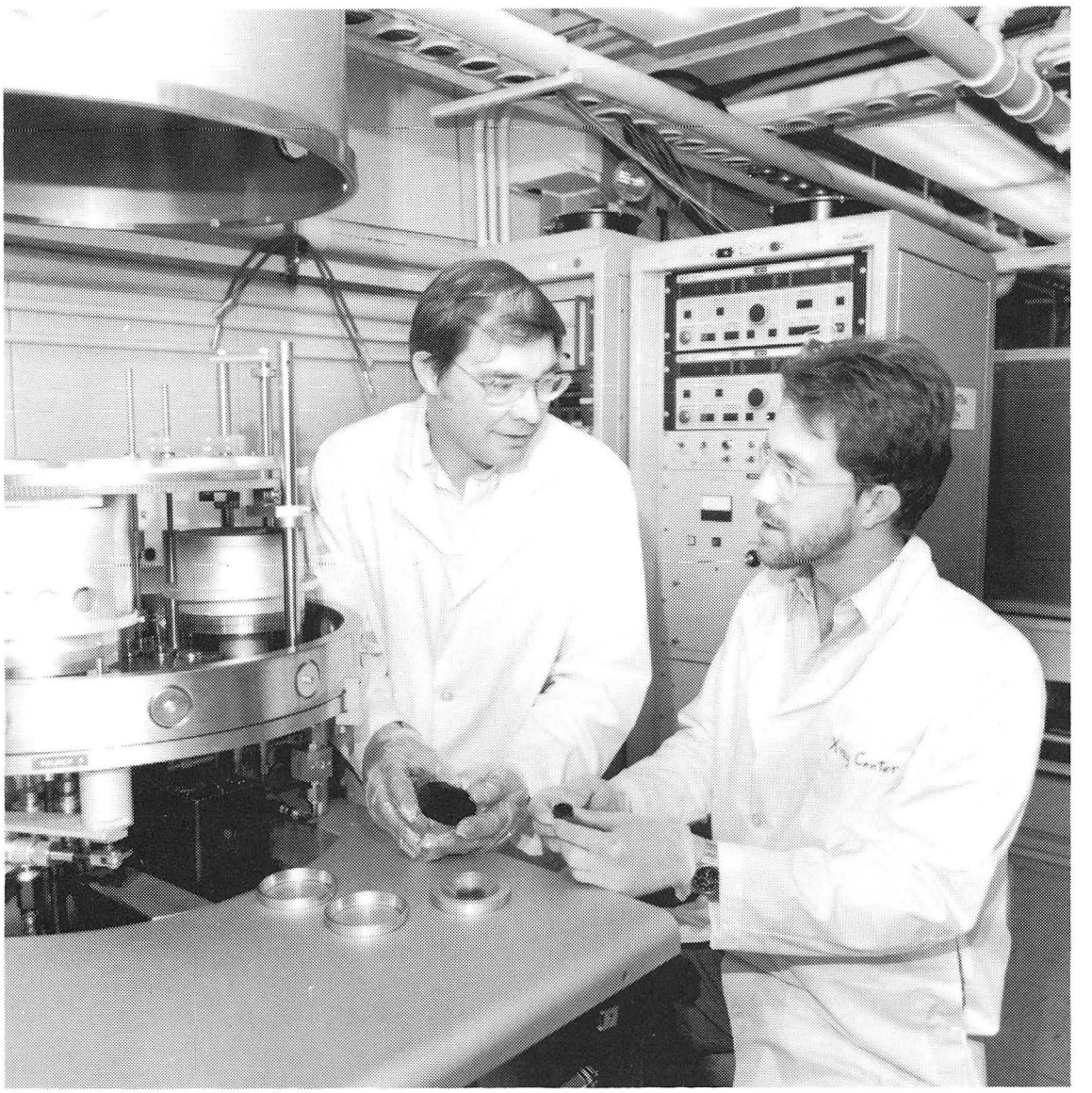
Mo/Si
d_p = 87.2 A
d_s = 86.6 A
λ = 161 A

Mo/Si Multilayer Mirrors for $h\nu \leq 100$ eV

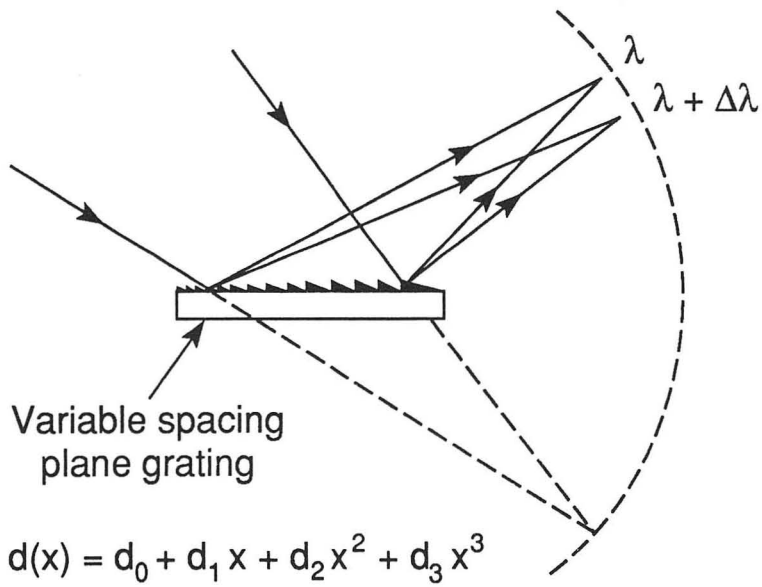
T.D. Nguyen, R. Gronsky, J.B. Kortright (CXRO/NCEM)



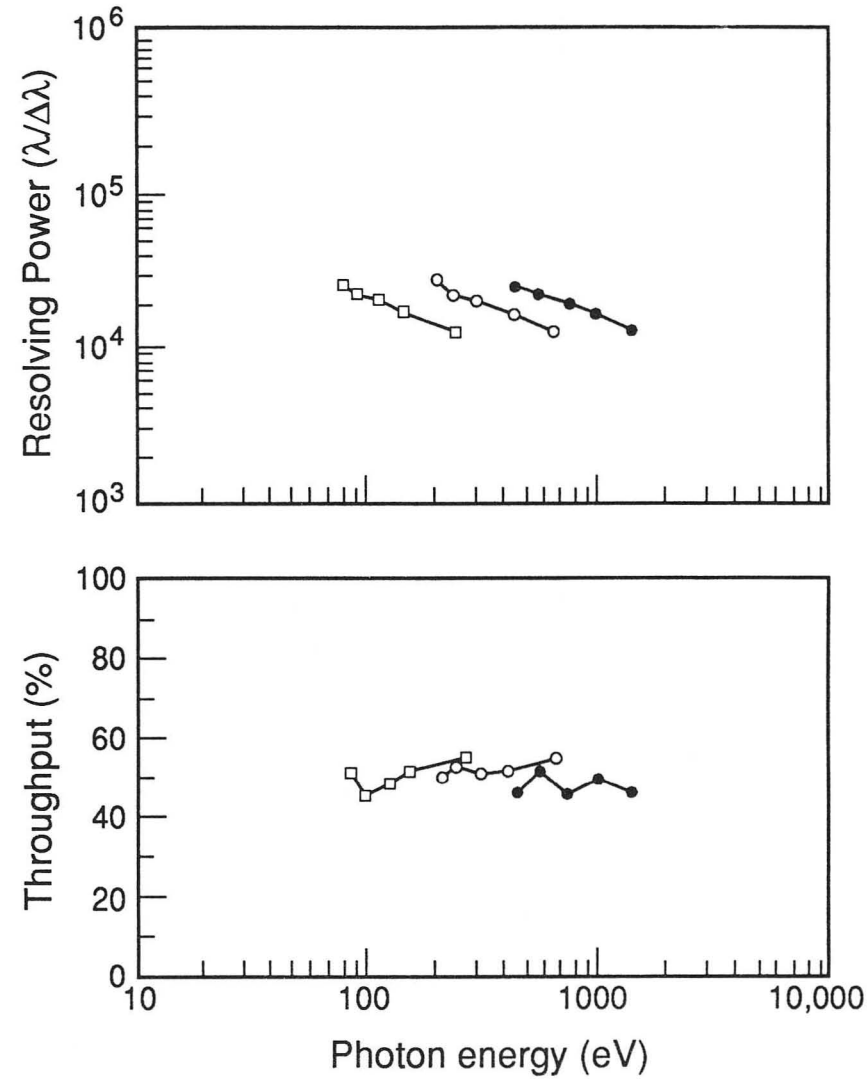
JEOL 200 CX — high resolution TEM — bright field image



New Monochromators and Spectrometers Based on Varied Line Space Gratings



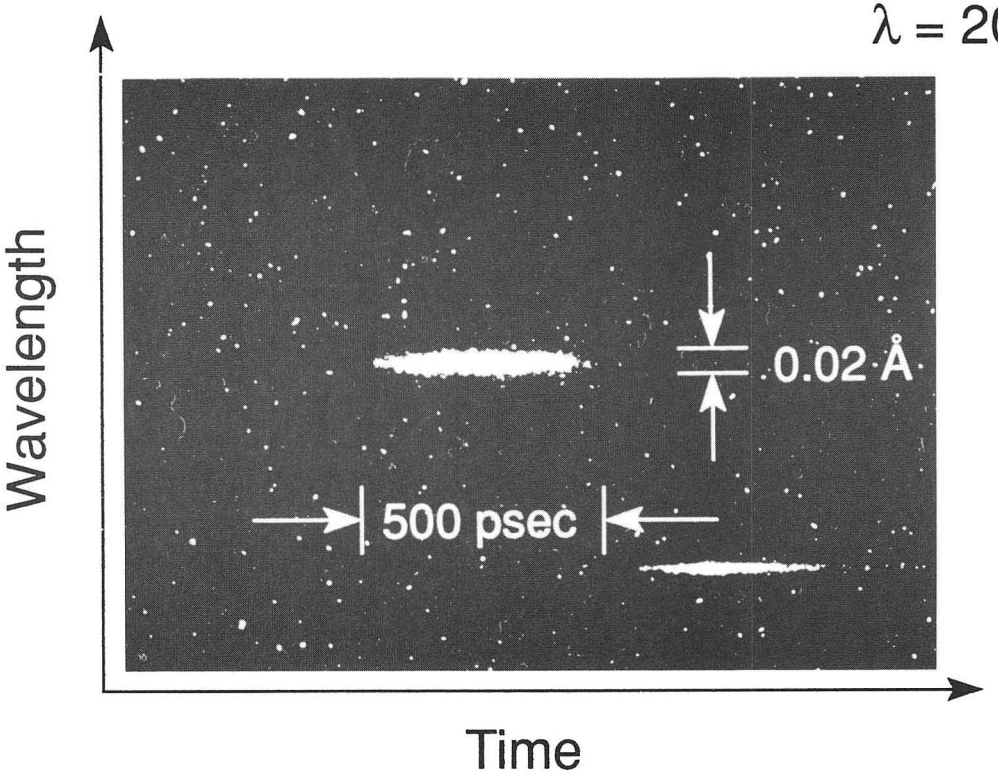
$$d(x) = d_0 + d_1 x + d_2 x^2 + d_3 x^3$$



- High resolving power
- High throughput
- Erect field
- Low cost features:
  - Simple scanning motion
  - Stationary slits
  - Stationary refocus mirrors
  - Simple optical surfaces

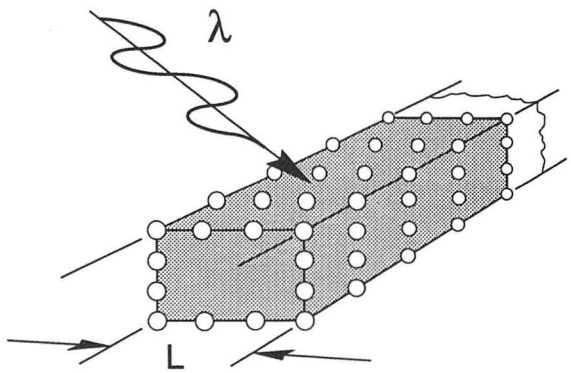
Time-Resolved X-Ray Laser Linewidth

Neon-like Selenium
$\lambda = 206.36$ Å

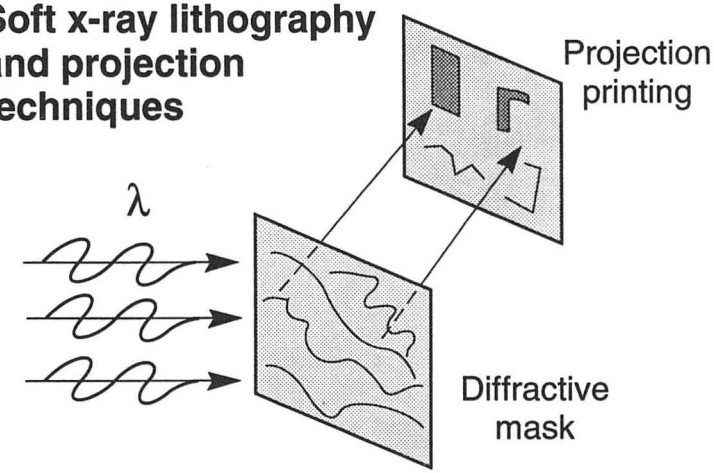


Coherent X-ray Techniques for the Physical Sciences

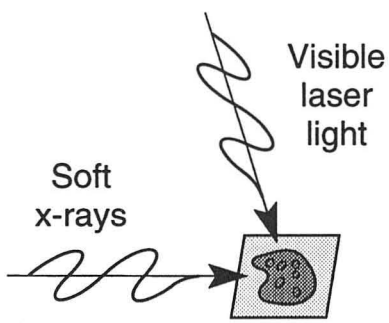
Resonant excitation of quantum electronic effects and fabrication of nanostructure patterns



Soft x-ray lithography and projection techniques

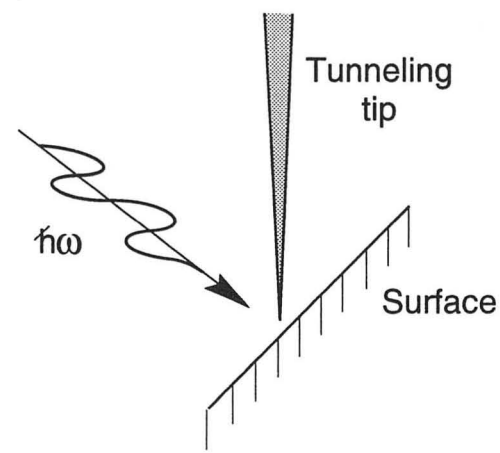


Non-linear soft x-ray optics



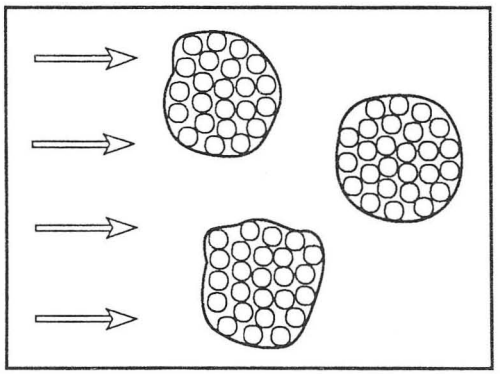
- Basic physics of non-linear devices
- Visible switching of x-ray phenomena
- Core level excitons in solids

Photon assisted tunneling by energy selective atomic pumping

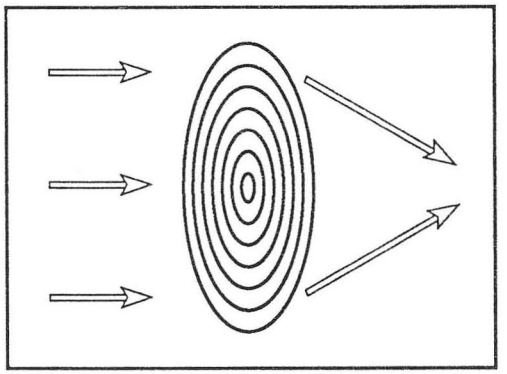


XBL 8911-6593

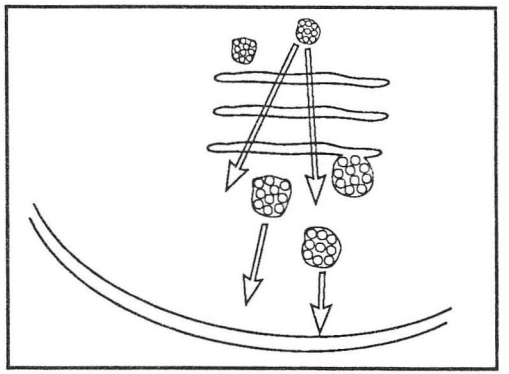
Applications to the Life and Physical Sciences (CXRO)



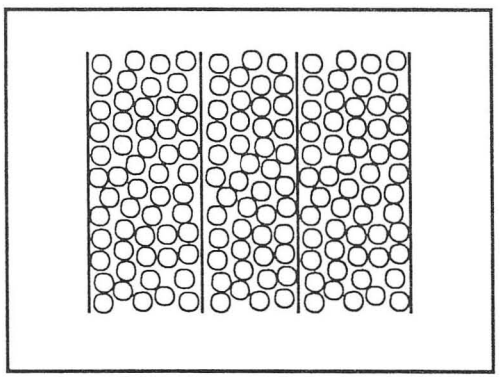
Structure and dynamics of transport vesicles



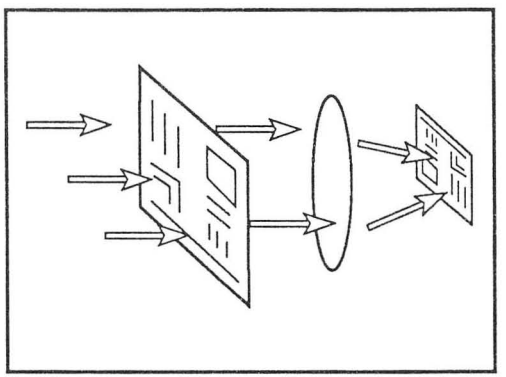
X-ray microscopy to 300 Å resolution



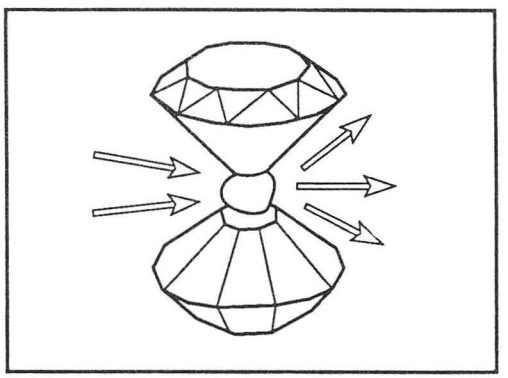
Intracellular transport processes



Stability of atomic interfaces



Reduction lithography to 0.1 μm feature size



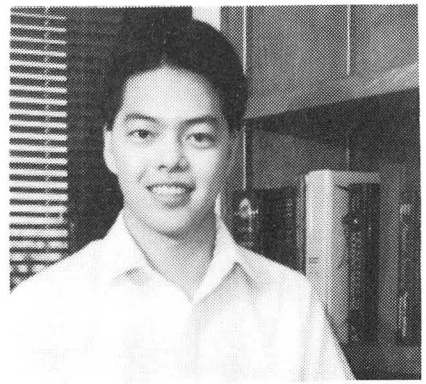
Phase transitions and structure in metalhydrides at terapascal pressures

XBL 905-5849

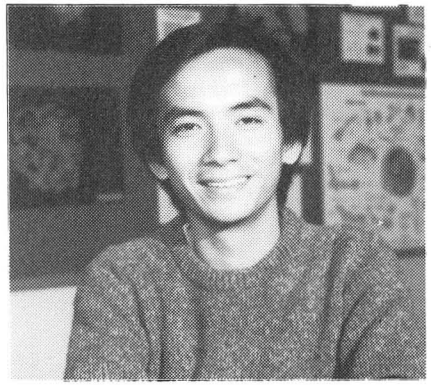
Graduate Students in CXRO

Kaarin Goncz
Dept. of Biophysics
U.C. Berkeley

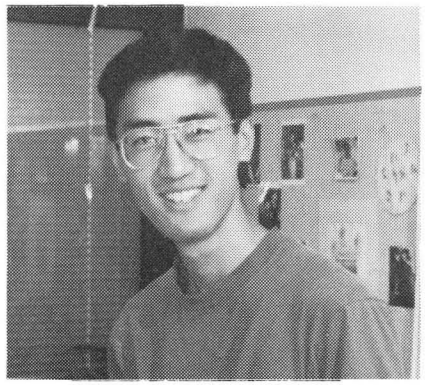
Nasif Iskander
In transition



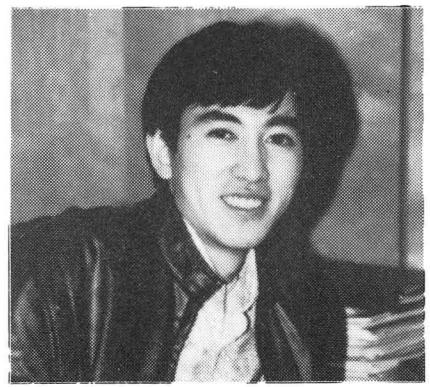
Bill Loo
In transition



Tai Nguyen
Dept. of Material Science
and Mineral Engineering
U.C. Berkeley

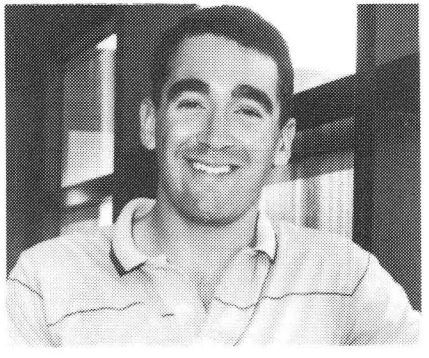


Max Wei
Dept. of Electrical Engineering
and Computer Sciences
U.C. Berkeley



Yan Wu
Dept. of Physics
U.C. Berkeley

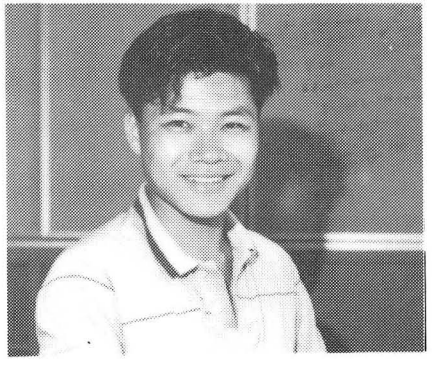
Undergraduate Students in CXRO



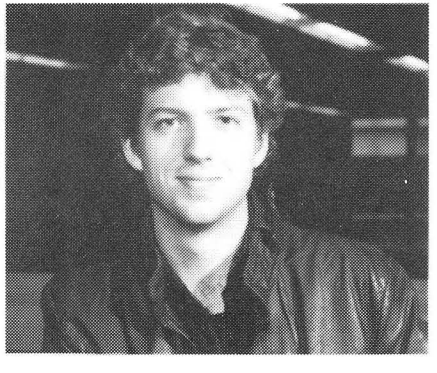
Eric Bolt
Dept. of Mathematics
U.C. Berkeley

Jon Chun
Dept. of Electrical Engineering
and Computer Sciences
U.C. Berkeley

Jeff Davis
Dept. of Physics and
Dept. of Applied Mathematics
U.C. Berkeley



Victor Liu
Dept. of Physics
U.C. Berkeley



Mark Thomas
Dept. of Physics and
Dept. of Applied Mathematics
U.C. Berkeley

Simie Turek
Dept. of Mathematics
U.C. Berkeley

Spring Semester - 1990

INTRODUCTION TO X-RAY PHYSICS AND TECHNOLOGY

E210
COURSE CONTROL # 25004
3 UNITS/LETTER GRADE

A NEW course exploring modern developments in the physics and applications of soft x-rays. Lectures will be geared toward both undergraduate and graduate students, with assignments appropriate to the student's status. Subject matter will include: generation of x-rays with laboratory tubes, synchrotron radiation, x-ray lasers, black-body radiation, and laser-plasma sources. Concepts of coherence and partial coherence, with examples at visible wavelengths (ruby lasers and holograms). Techniques for the generation of partially coherent radiation at extreme ultraviolet and x-ray wavelengths, including x-ray lasers, and relativistic electrons interacting with periodic magnet structures (undulators). X-ray interaction with matter, atomic scattering factors, refractive index. Reflective optics, imaging systems, microscopes and telescopes. Interference coatings. Diffractive optics, including slits, gratings and zone plates. Resolution of imaging and dispersive systems. Use of crystals. Zone plate x-ray microscopy resolved to 500A. Element and chemical sensitivity. Coherence requirements, relation to undulators and interference coatings. X-ray holography, reconstruction, early experiments. X-ray interferometry with crystals, gratings and interference coatings. Applications to plasma physics, short wavelength lasers, biology and medicine, material and chemical sciences, lithography.

Prerequisites: Upper division or graduate standing or consent of instructor.

Time: Tuesdays and Thursdays, 2:00 - 3:30 p.m.
240 Bechtel

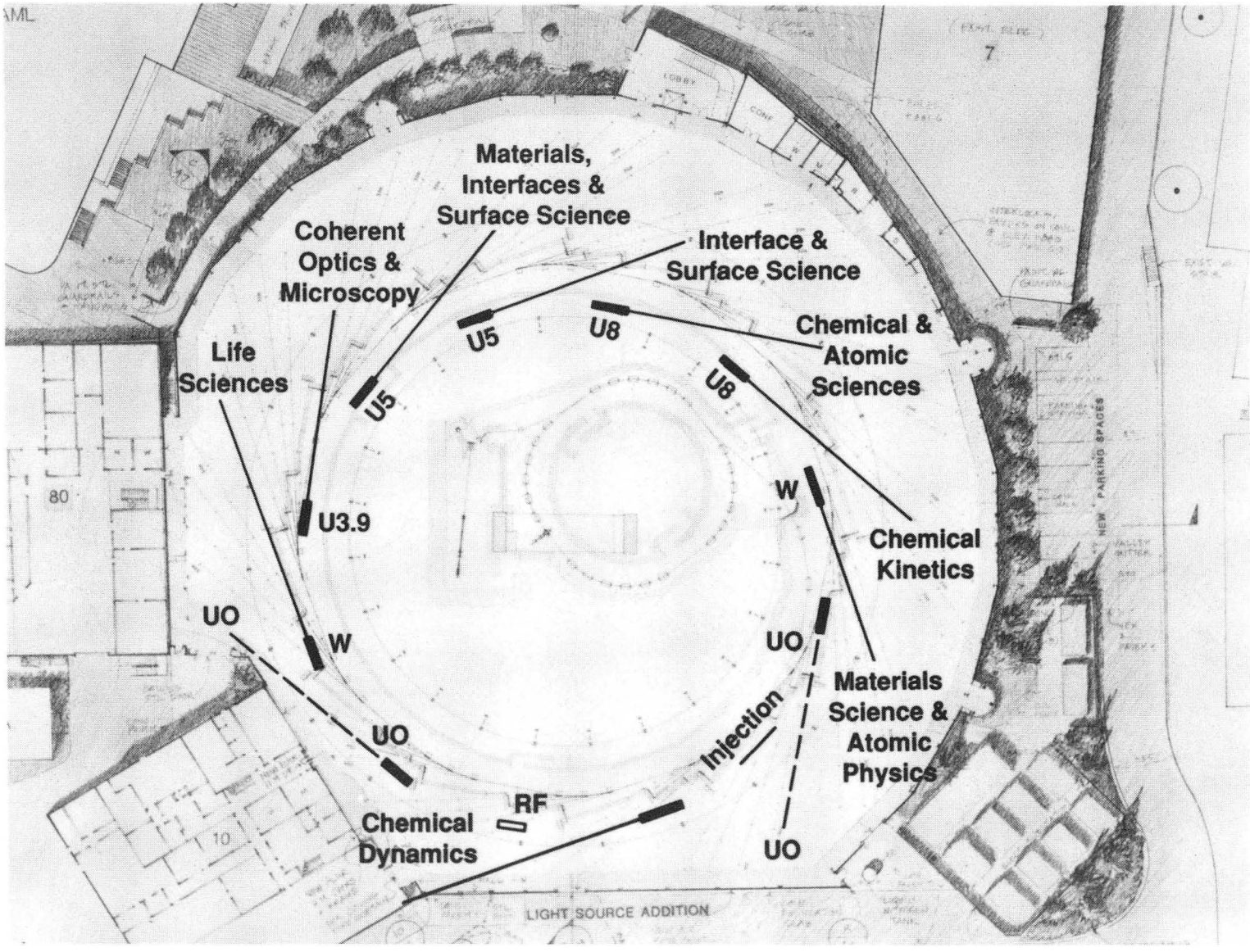
Sponsored by:

College of Engineering
Interdisciplinary Studies Center
230 Bechtel Engineering Center, UCB

If you are interested in obtaining enrollment in this course contact Dr. Attwood at 486-4463

Official University Poster

Science and Technology at the Advanced Light Source



THE ADVANCED LIGHT SOURCE: ON SCHEDULE FOR 1993

Jay Marx

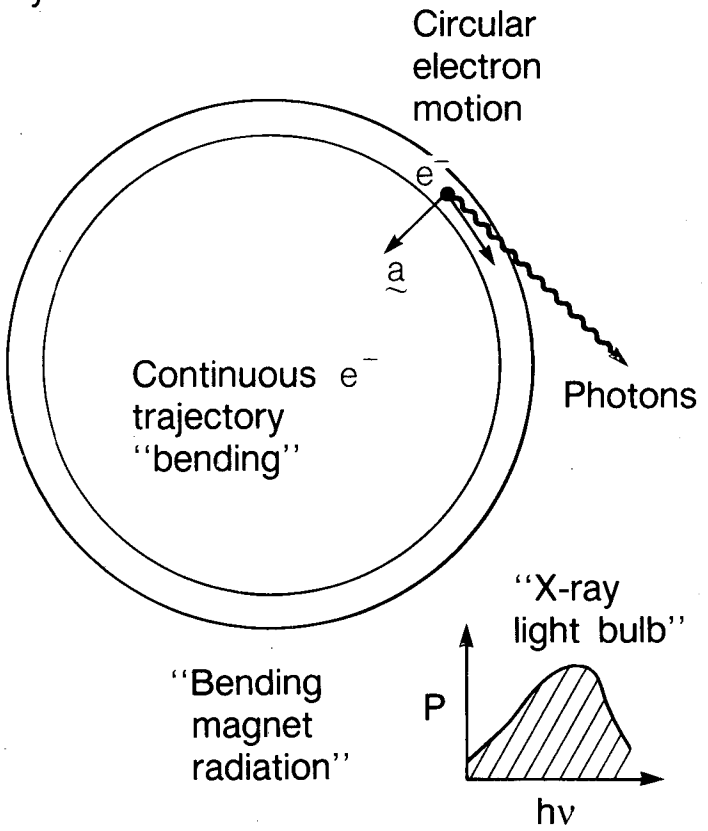
Advanced Light Source
Lawrence Berkeley Laboratory

What is the Advanced Light Source (ALS)?

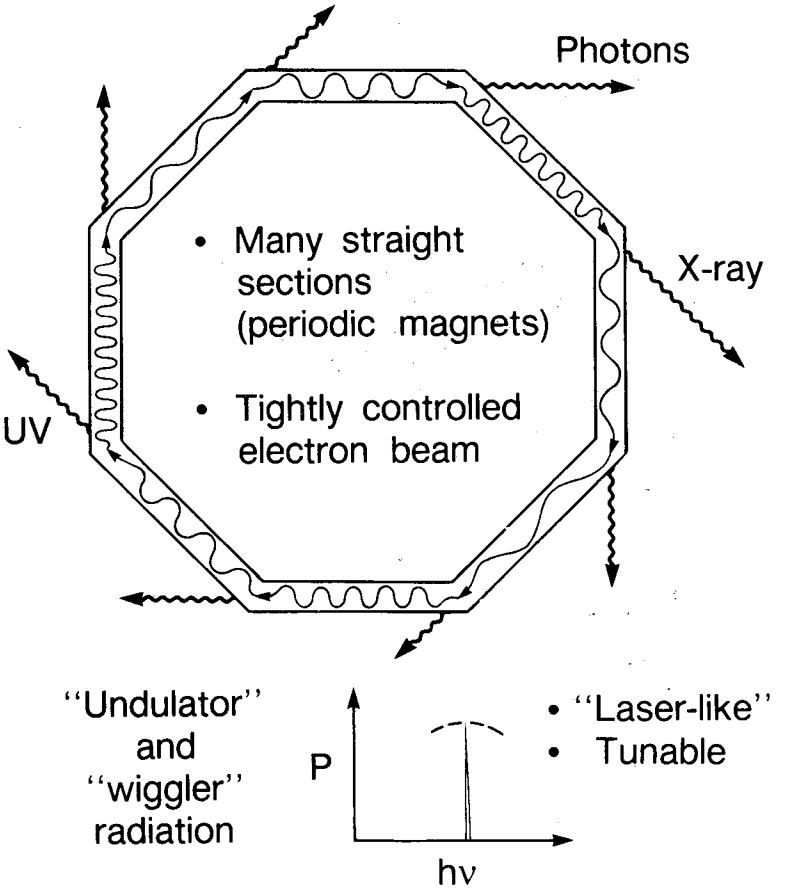
- National user facility
- Provides UV and soft x-ray beams of unprecedented brightness
  - Broadly tunable with narrow spectral features
  - Partially coherent
  - 30 psec time structure
- Utilized by researchers from industry, academic, and national laboratory communities
  - Technology (e.g., projection lithography)
  - Materials and surface science
  - Atomic and molecular physics
  - Chemistry
  - Life sciences
- Construction project began in late 1986
- Begin operations in spring 1993
- Construction cost — $99.5 million

Evolution of Synchrotron Radiation

Todays Synchrotrons:

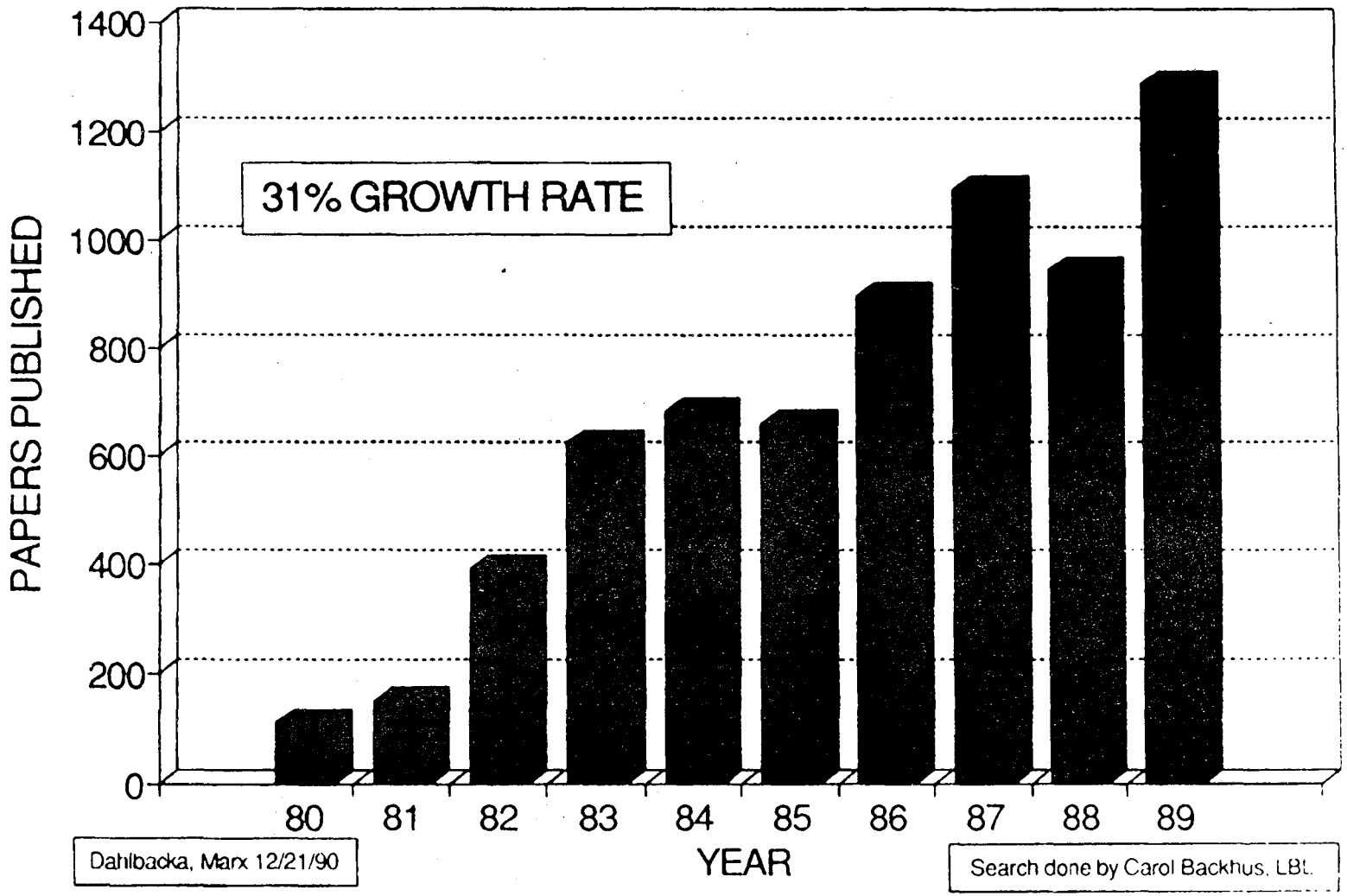


Tomorrows Synchrotrons:



XBL 888-8937

RAPID GROWTH IN PUBLICATIONS USING SYNCROTRON RADIATION



The Advanced Light Source: New Capabilities, New Research

ALS

Next-Generation VUV Synchrotron Radiation Facility Optimized for Insertion Devices

- INTENSITY, "BRIGHTNESS"
- LASERLIKE COHERENCE
- SHORT PULSES (30 trillionths of a second)
- TUNABILITY

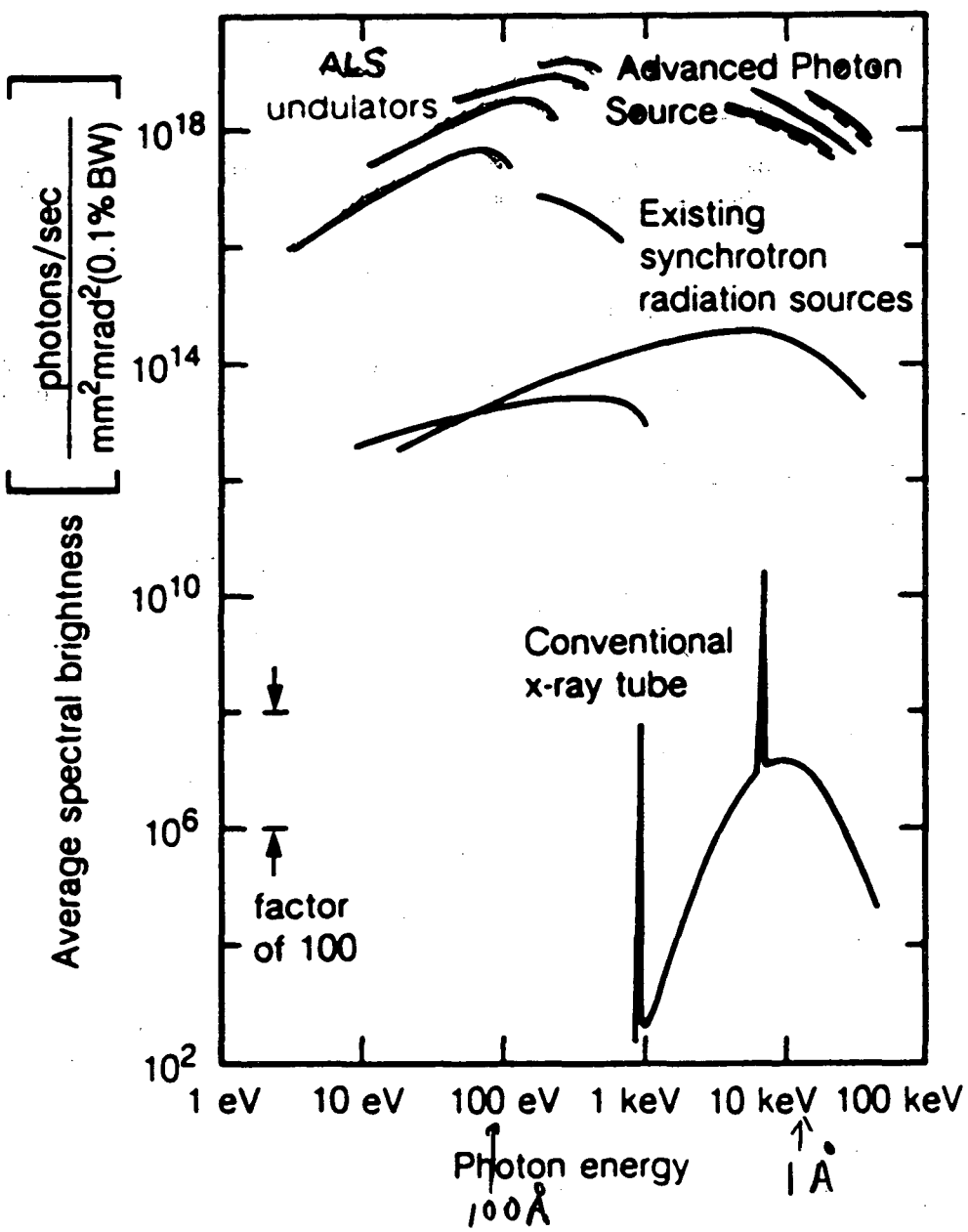
⇒

- Biological imaging
- Measurements on small or dilute samples
- Studies of ultrafast processes
- Studies of dynamic processes in biological systems
- Bond-selective chemistry
- High-spatial-resolution studies
- Lithography for chip fabrication

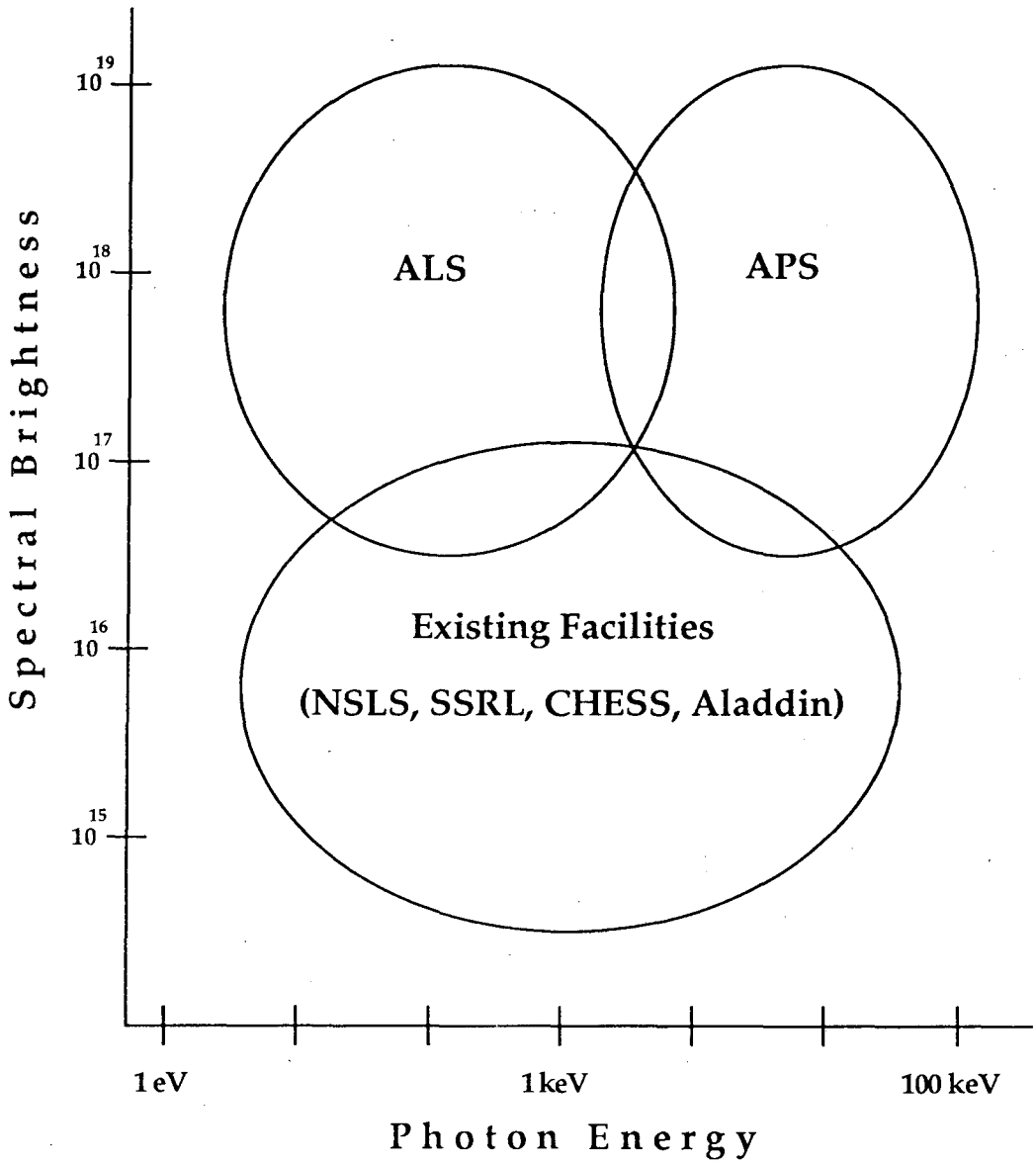
Brightness

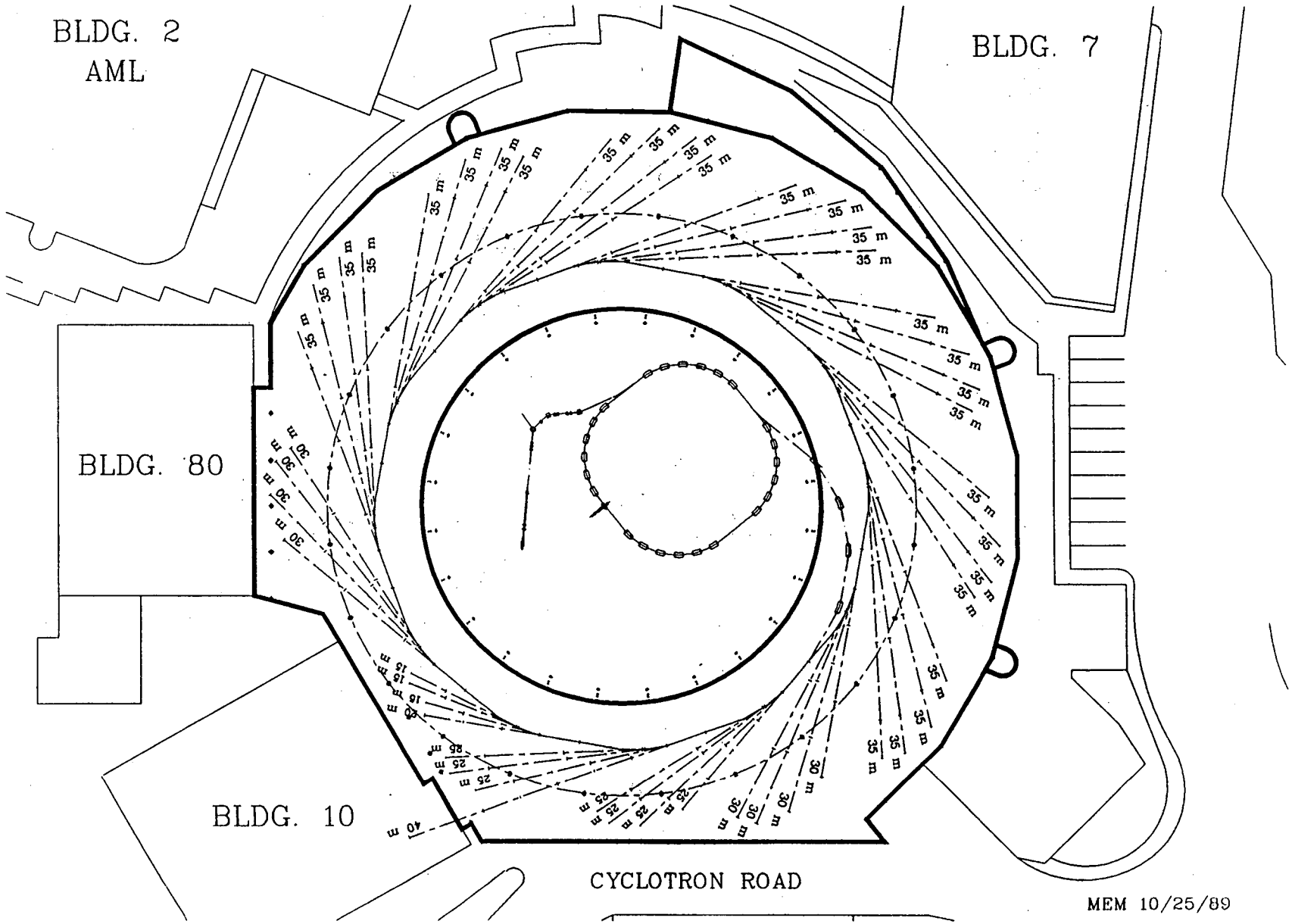
- intensity
- narrowness of spectral distribution
- ease of focussing

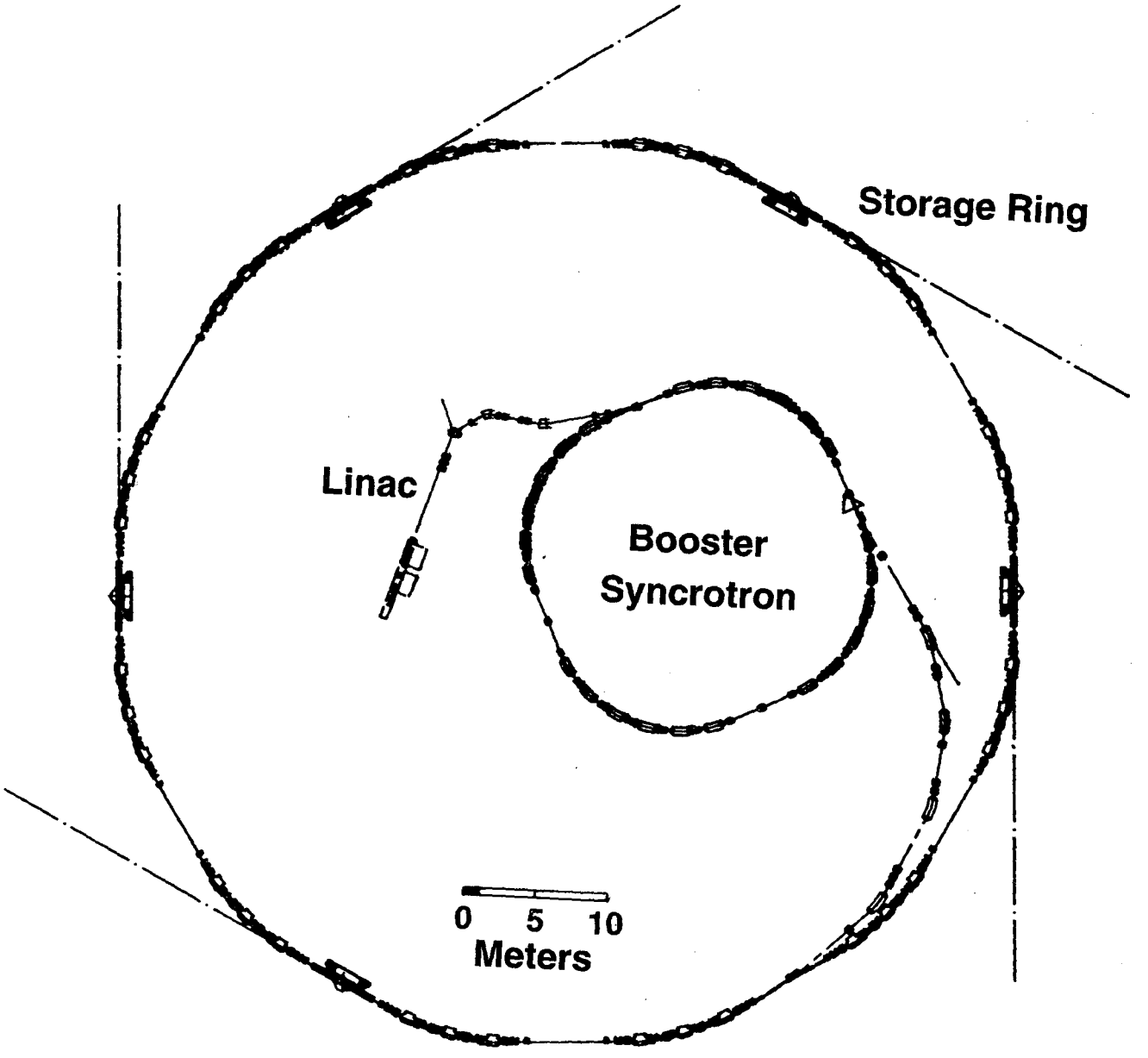
Brightness: an important measure of quality



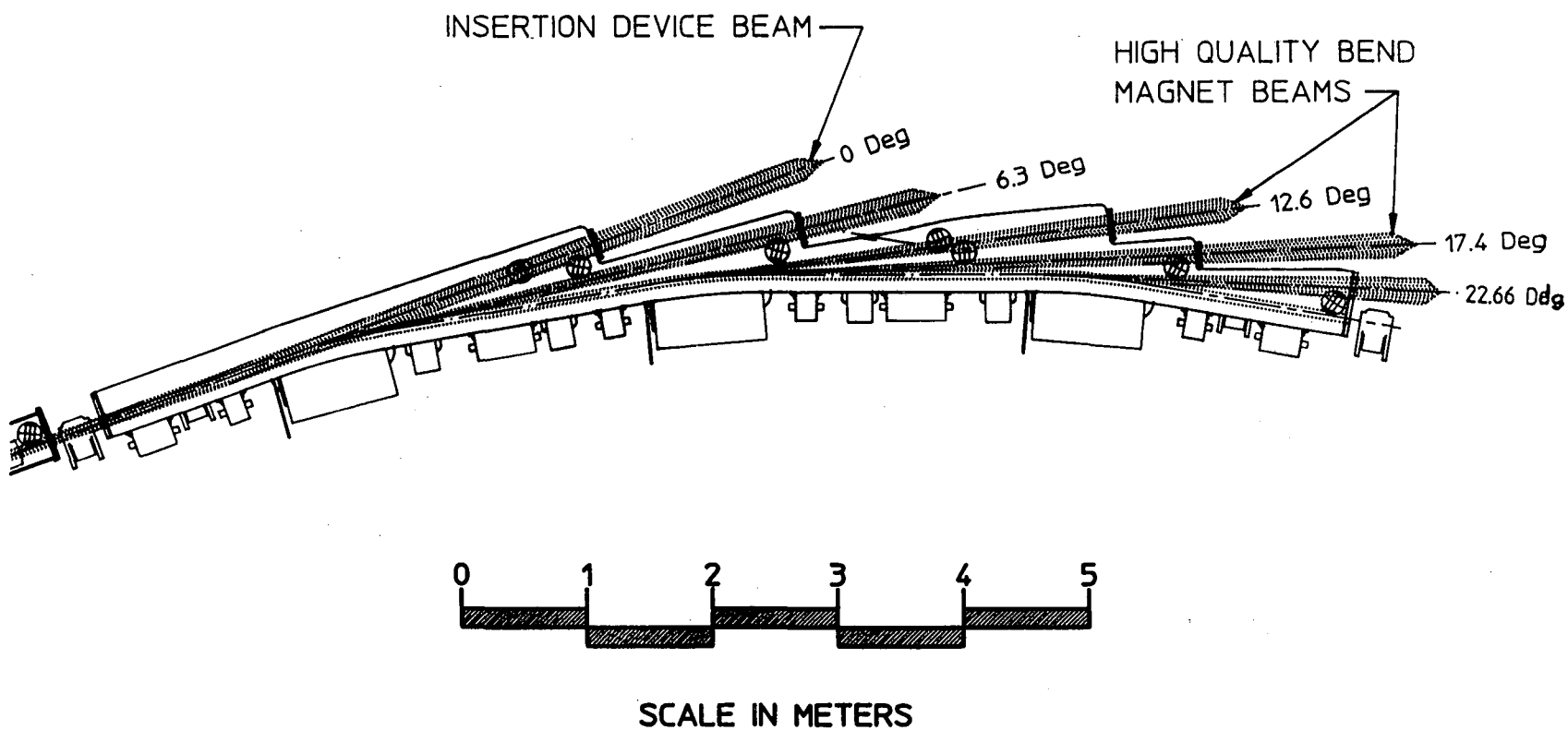
The U.S. Scene


Spectral Brightness
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
ALS
APS
Existing Facilities
(NSLS, SSRL, CHESS, Aladdin)
1 eV
1 keV
100 keV
Photon Energy


BLDG. 2
AML
BLDG. 7
BLDG. 80
BLDG. 10
CYCLOTRON ROAD
MEM 10/25/89


Storage Ring
Linac
Booster
Syncrotron
0 5 10
Meters

ALS PHOTON BEAM CAPABILITIES



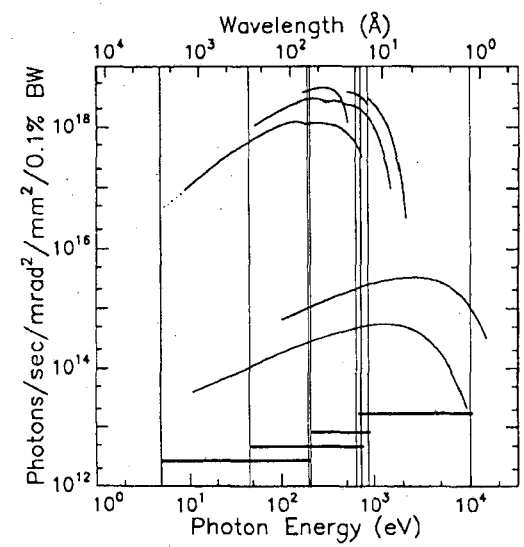
User Relations and the Scientific Program

- We are making good progress towards a balanced, strong scientific program for ALS
- Through workshops, the scientific/technical community helped shape capabilities designed into the ALS
- Users' Executive Committee of ALS Users' Association:
  - Elected group representing interest of broad user community
- Science Policy Board
  - Reporting to LBL Director
  - Chaired by Dean Eastman (IBM)
  - W.F. Brinkman (AT&T) is new member
- Program Review Panel

— CHAIRED BY NEVILLE SMITH (AT&T)

Initial Approved Program

- Broad program
  - Photon wavelength: 5 eV – 10,000 eV
  - Many research disciplines
  - Researchers from many institutional settings
- Insertion Device Program
  - 1 x U10 Combustion Dynamics
  - 2 x U8 Chemistry and Atomic Physics
  - 3 x U5 Surface and Materials Science
  - 1 x U3.9 X-ray Imaging and Optics
  - 2 x W Materials Science/Life Science



- This program will require substantial user funding to supplement ALS project funds.
- Bend Magnet Program
  - Bend magnets not emphasized in initial proposal solicitation
  - IDTs want 5 bend-magnet lines
  - Bend-magnet proposals considered by PRP on June 6, 1990; 4 approved
  - Strong response to recent solicitation for interested researchers; many new proposals expected in next year

Participating Research Teams (PRTs)

- PRTs receive privileged access to ALS beamline
- Project and users can share costs *up to monochromator exit*

  Type A: Project pays all costs

  Type B: Shared costs

  Type C: User pays all costs

- PRTs responsible for apparatus after monochromator exit
- Type B PRTs: leverage of project funds
- Type B PRTs need time
- Initial Participating Research Teams (PRTs) for insertion devices have been formed; there are still a few unassigned straight sections
- PRTs for utilization of bend magnet radiation are still being formed

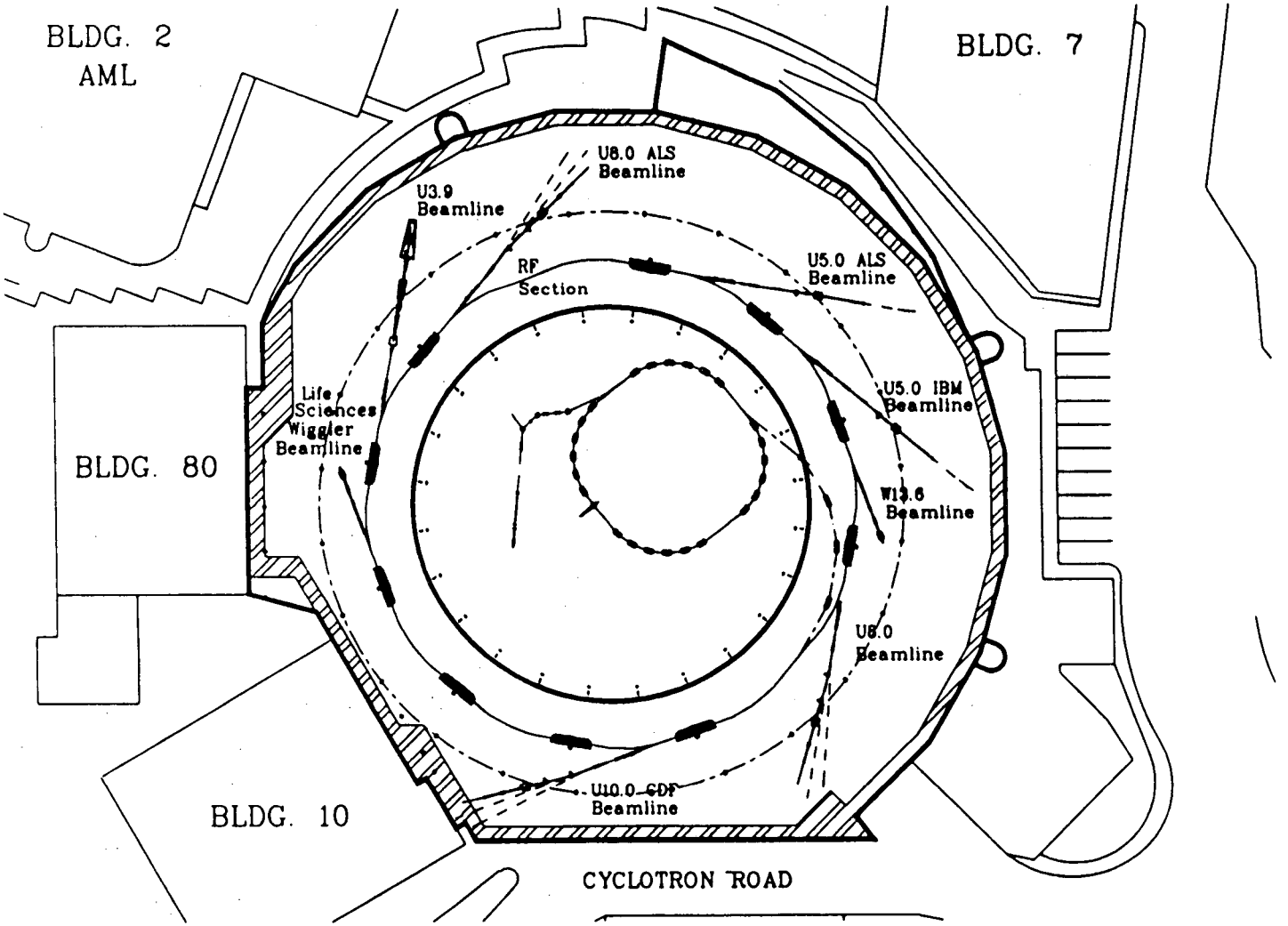
Access To ALS

- Open to all qualified users
- Proposals evaluated by peer review (Program Review Panel)
- No user fees for research published in open literature and supportive of the broad mission of DOE
- Full cost recovery for proprietary research

Advanced Light Source

- $99.5 million synchrotron radiation source scheduled for completion in 1993.
- Provide VUV and soft x-ray beams for up to 60 experimental stations for materials science, chemistry, biology, and industrial research.
- National user community organized and has generated initial user proposals.
- ALS will be major new focus of LBL activities.

Beamline Layout: Advanced Light Source



Jan 1990

Further Information About the ALS

- All registered participants will be added to ALS mailing list
- ALS newsletter several times per year
- ALS Handbook can be requested
- Join or form a research group:

<u>Contact</u>:

Fred Schlachter
Scientific Program Coordinator
Advanced Light Source
MS 46-161
Lawrence Berkeley Laboratory
Berkeley, CA 94720

AN ALS UNDULATOR BEAMLINE

Tony Warwick

Advanced Light Source
Lawrence Berkeley Laboratory

AN ALS UNDULATOR BEAMLINE

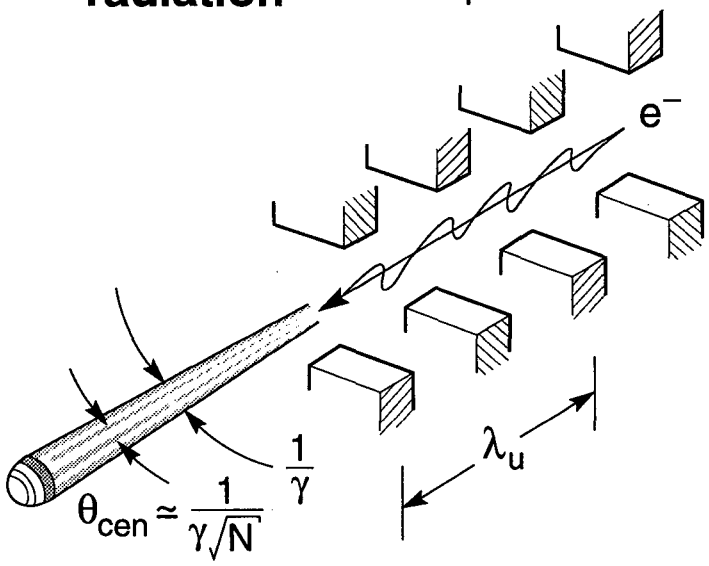
for:

- high resolution spectroscopy
- microscopy

showing:

- properties of undulator beam
- thermal load
- optical tolerances
- engineering
- cost

Undulator radiation

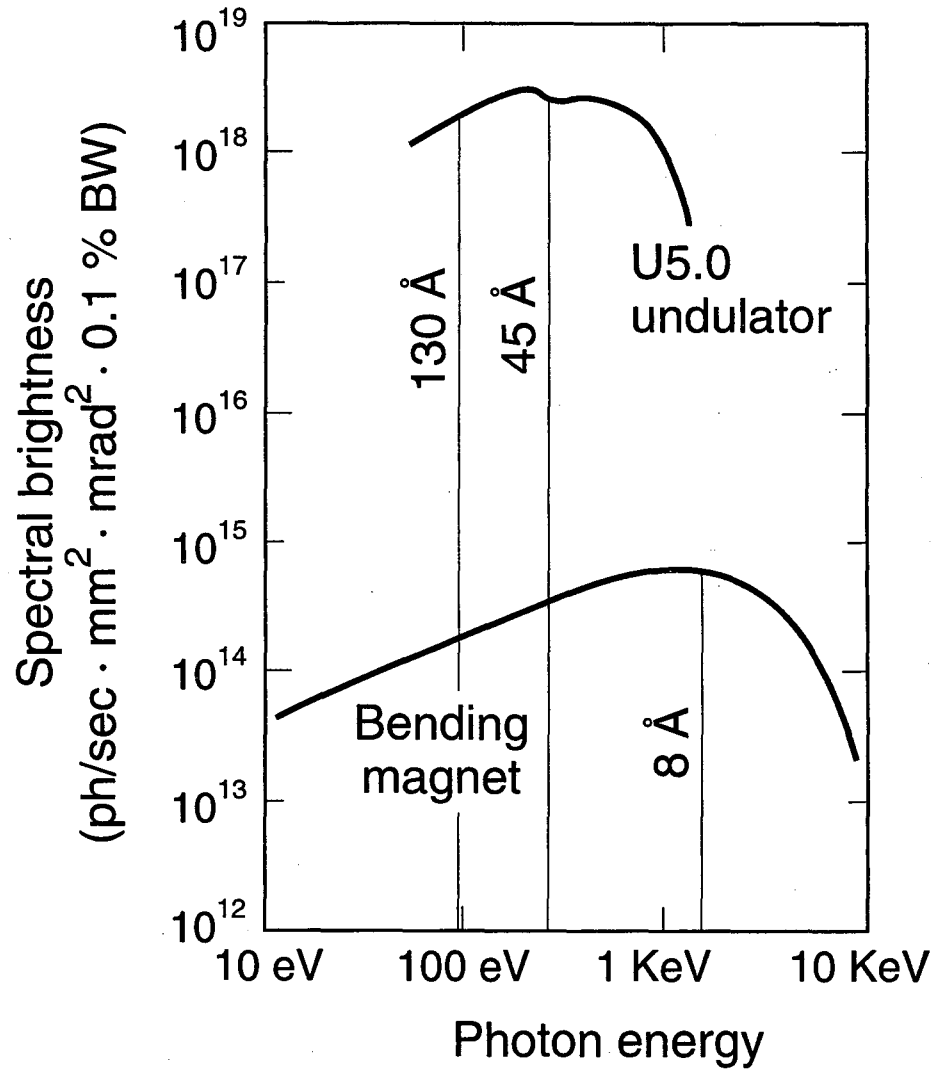


$$\lambda_x = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

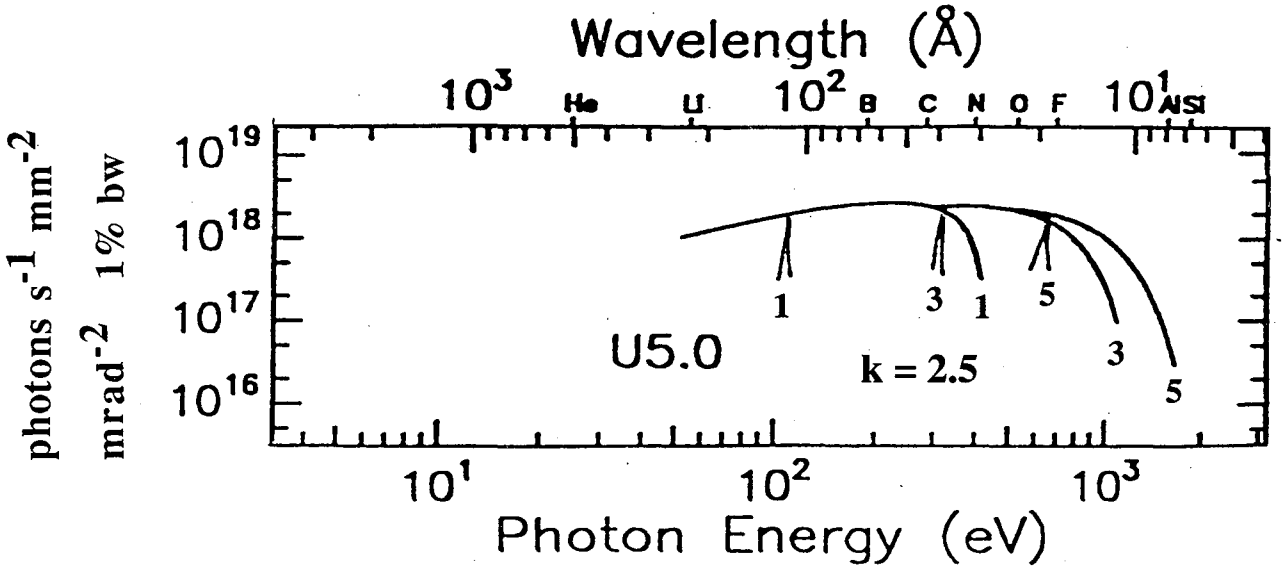
in the central radiation cone:

$$\frac{\Delta\omega}{\omega} \simeq \frac{1}{N}$$

$$\theta_{cen} \simeq \frac{1}{\gamma\sqrt{N}}$$

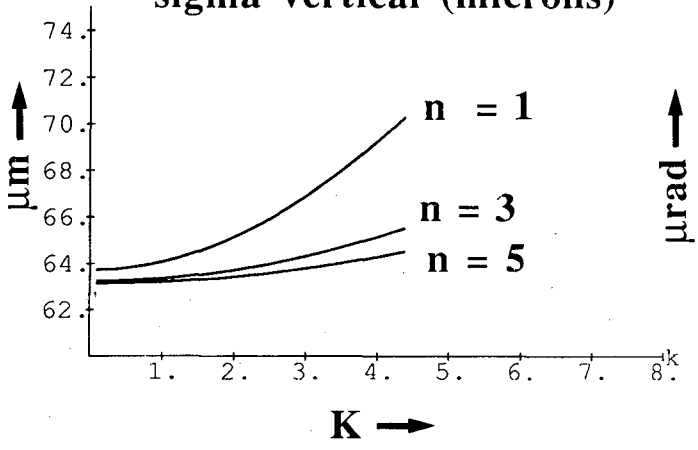


An undulator is a bright source, tunable by changing the magnet gap.



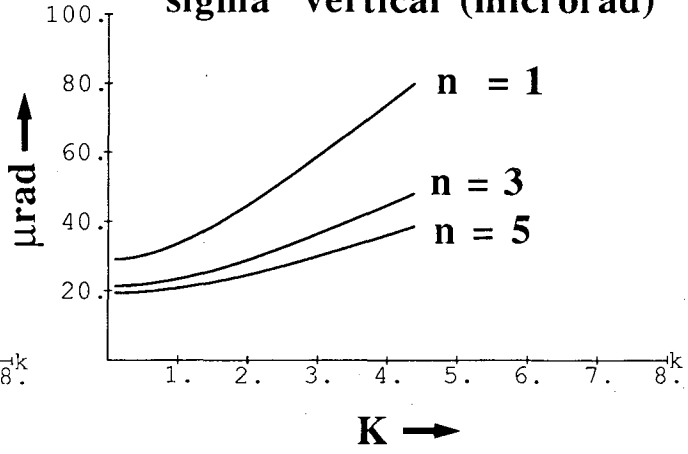
Source size

sigma vertical (microns)

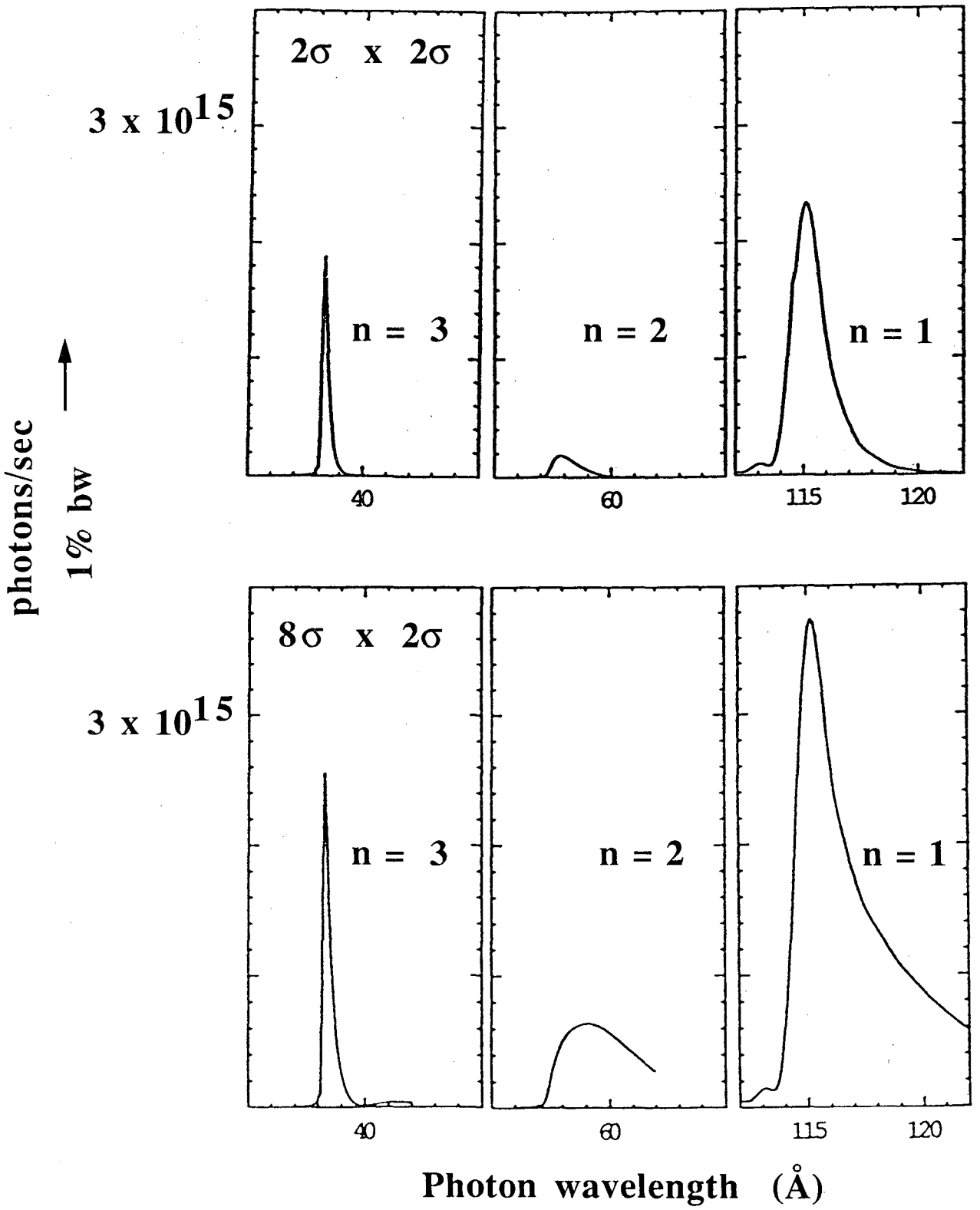


Source divergence

sigma' vertical (microrad)



Photons from ALS U5 undulator through rectangular aperture, K = 2.5



Undulator Beamline Projects Relevant to the Development of X-ray Lithography

- State-of-the-art source for high spectral brightness, partially coherent soft x-ray generation in a relatively narrow bandwidth (1-3%), narrow radiation cone (~40 μrad)

- Test facility for advanced soft x-ray imaging systems which benefit from relatively high power (~1 Watt) and partial coherence ($\ell_{coh} \cong 1$ μm and 10 times diffraction limited, for $\lambda = 130$Å and 1% bandwidth)

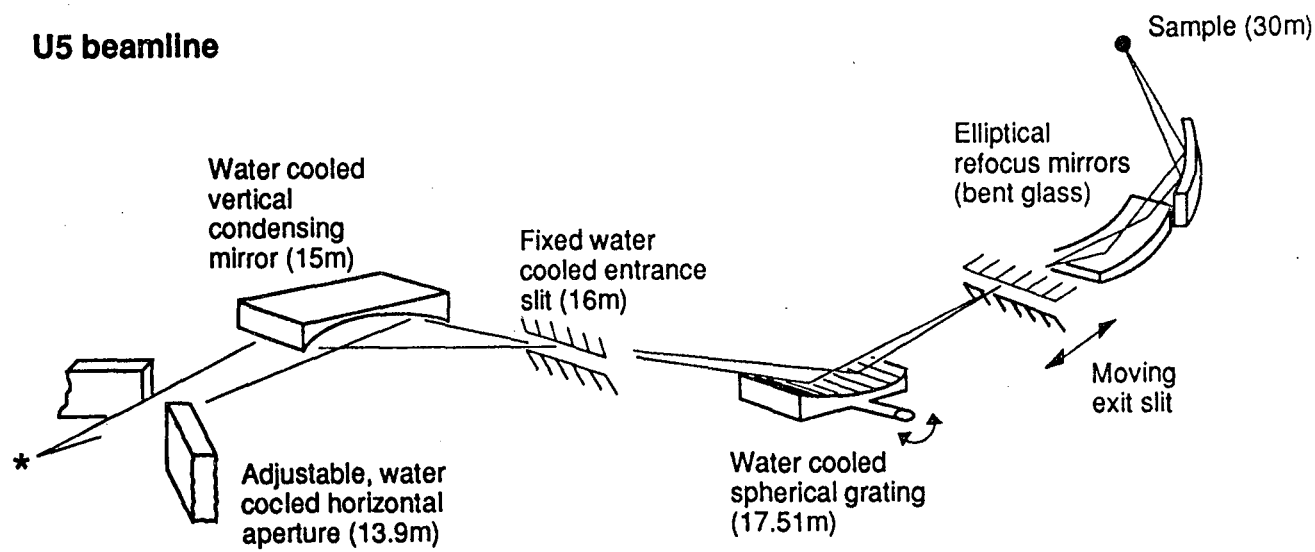
- Unique analytic tool for spatially resolved elemental studies studies of dilute dopants and impurities using zone plate focusing (400Å spot size) and highly monochromatized ($\lambda/\Delta\lambda \sim 10^4$) undulator radiation: photoelectron and emission spectroscopies.

Projects That Might Benefit X-ray Lithography Using a Bending Magnet Beamline at the ALS

- Development of a soft x-ray "metrology beamline", relevant to x-ray lithography

- A relatively inexpensive facility for resist, mask, and other project research and development; readily available to university and industrial members of an appropriate consortium

- A lithography test stand for optical systems research over a broad spectral range


U5 beamline
Sample (30m)
Elliptical
refocus mirrors
(bent glass)
Water cooled
vertical
condensing
mirror (15m)
Fixed water
cooled entrance
slit (16m)
Moving
exit slit
Adjustable, water
cocled horizontal
aperture (13.9m)
Water cooled
spherical grating
(17.51m)

Thermal Loads on ALS-U5 Beam Line Optics

Advanced Light Source

1.5 Gev, 400 mA, K= 4.0

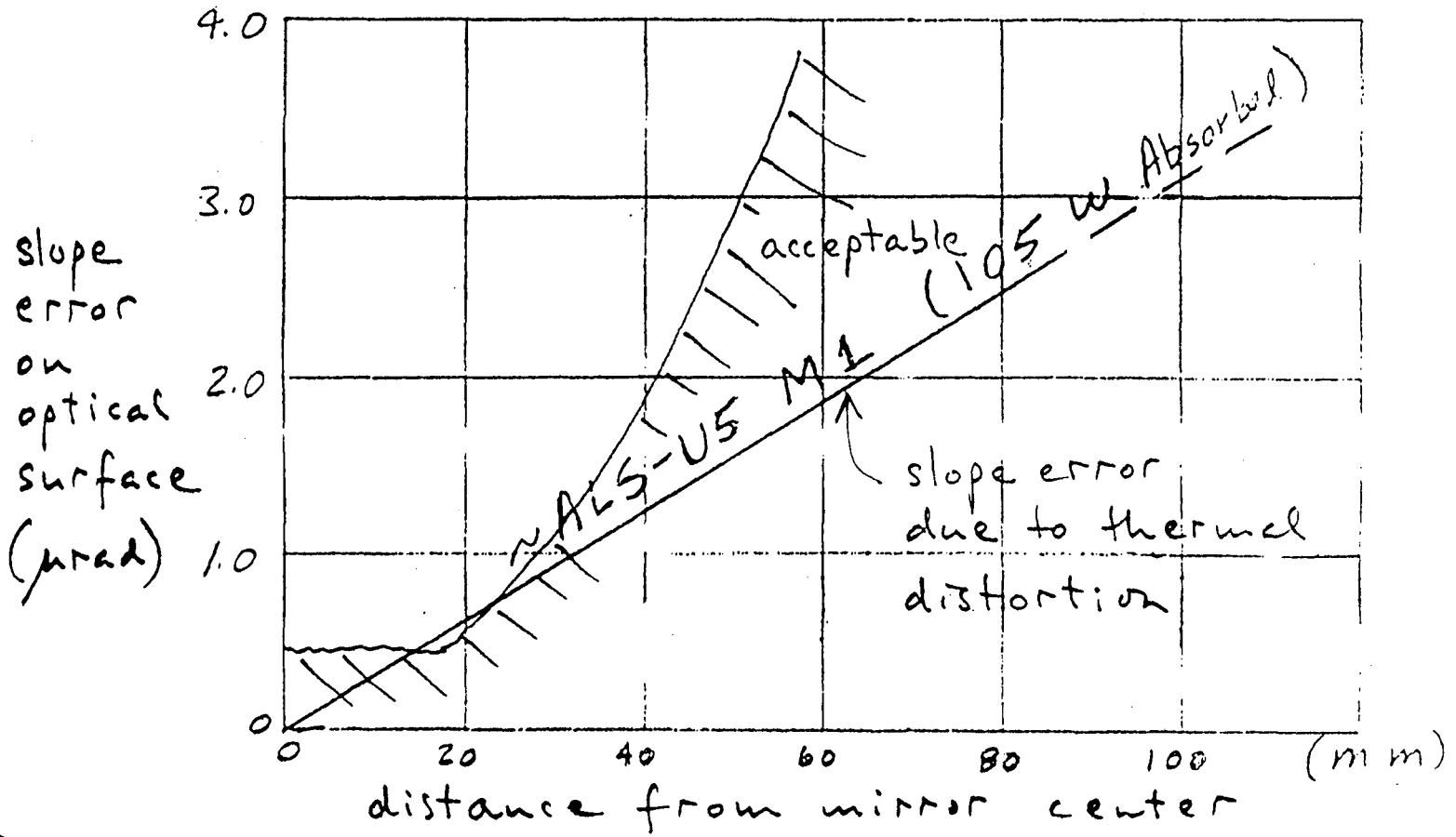
Undulator Total Power	1700 W
HBDA Aperture @ +/- 0.15 mrad (4 sigma)	
HBDA Incident Power	1540 W
M1 Mirror Incident Power	156 W
M1 Mirror Absorbed Power	106 W
Entrance Slit Incident Power (= Grating Max. Incident Power)	50 W
Grating Max. Absorbed Power	29 W

12/14/90

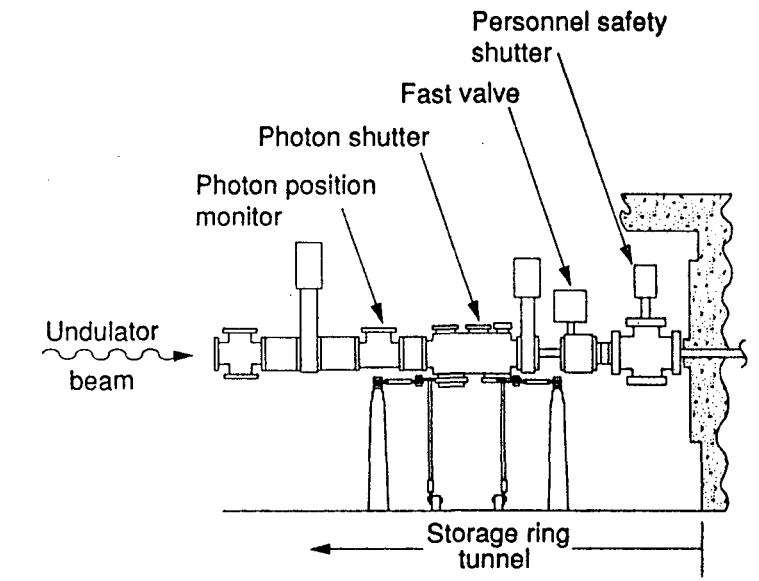
ALS-U5 Optics Estimated Thermal Distortion

M1 Mirror and Grating Slope Errors with Maximum Thermal Loads

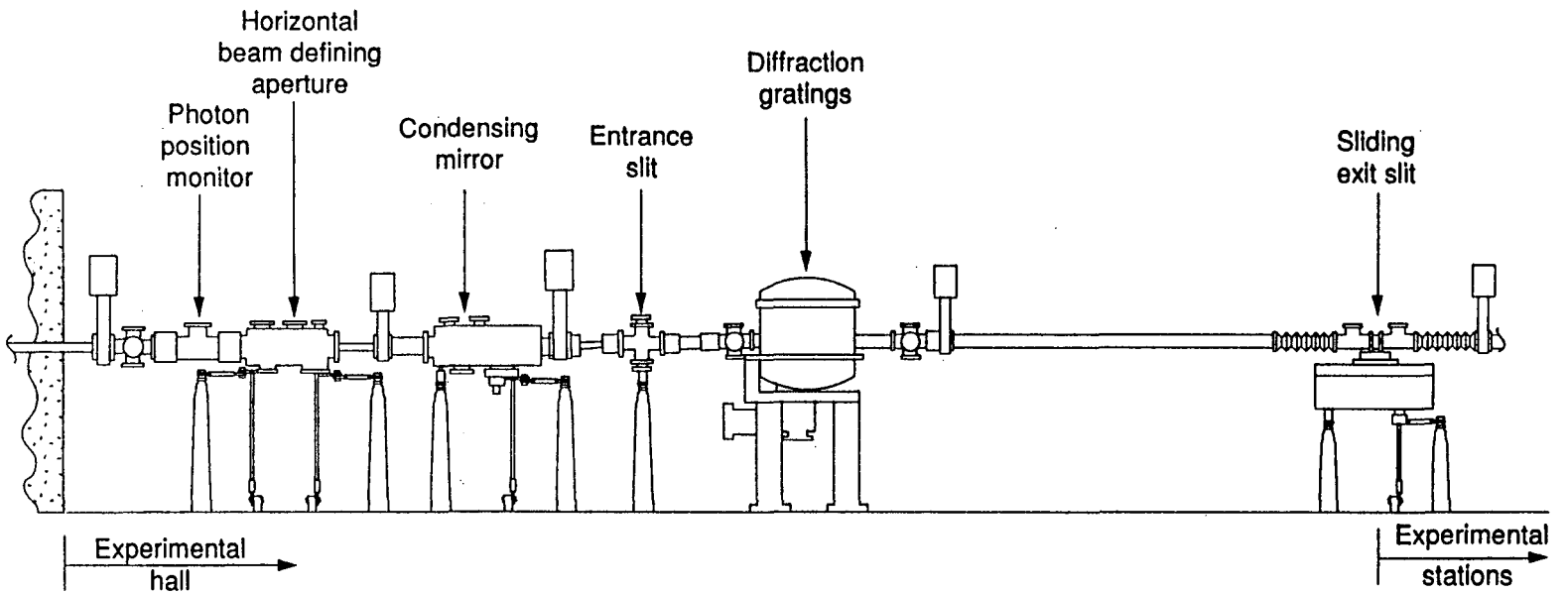
1.5 GeV, 400 Ma, K=4, HBDA @ +/- 0.15 mrad (4 sigma)



12/14/90

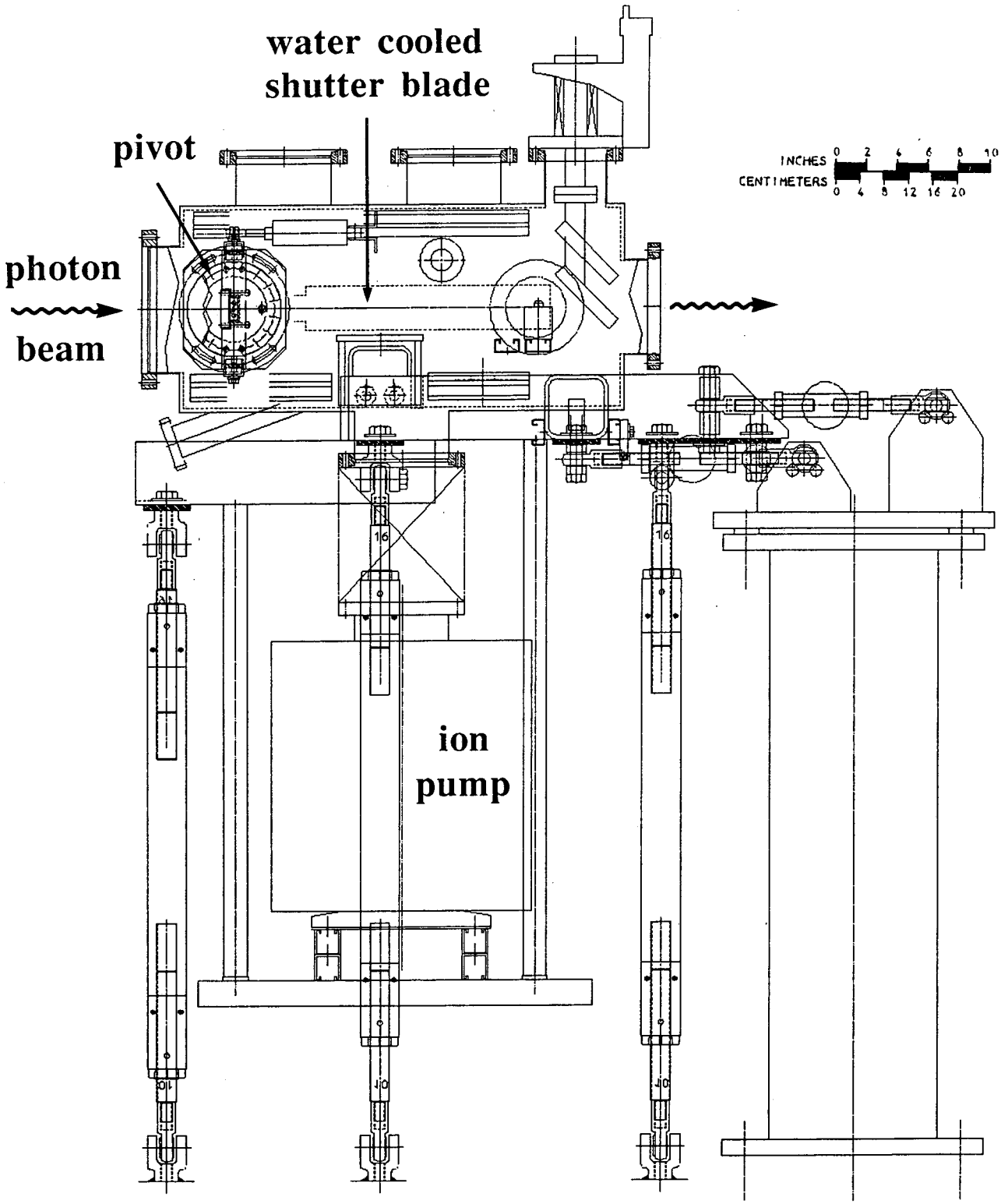


Spherical Grating Monochromator Beam Line for a 5 cm Period Undulator at the ALS

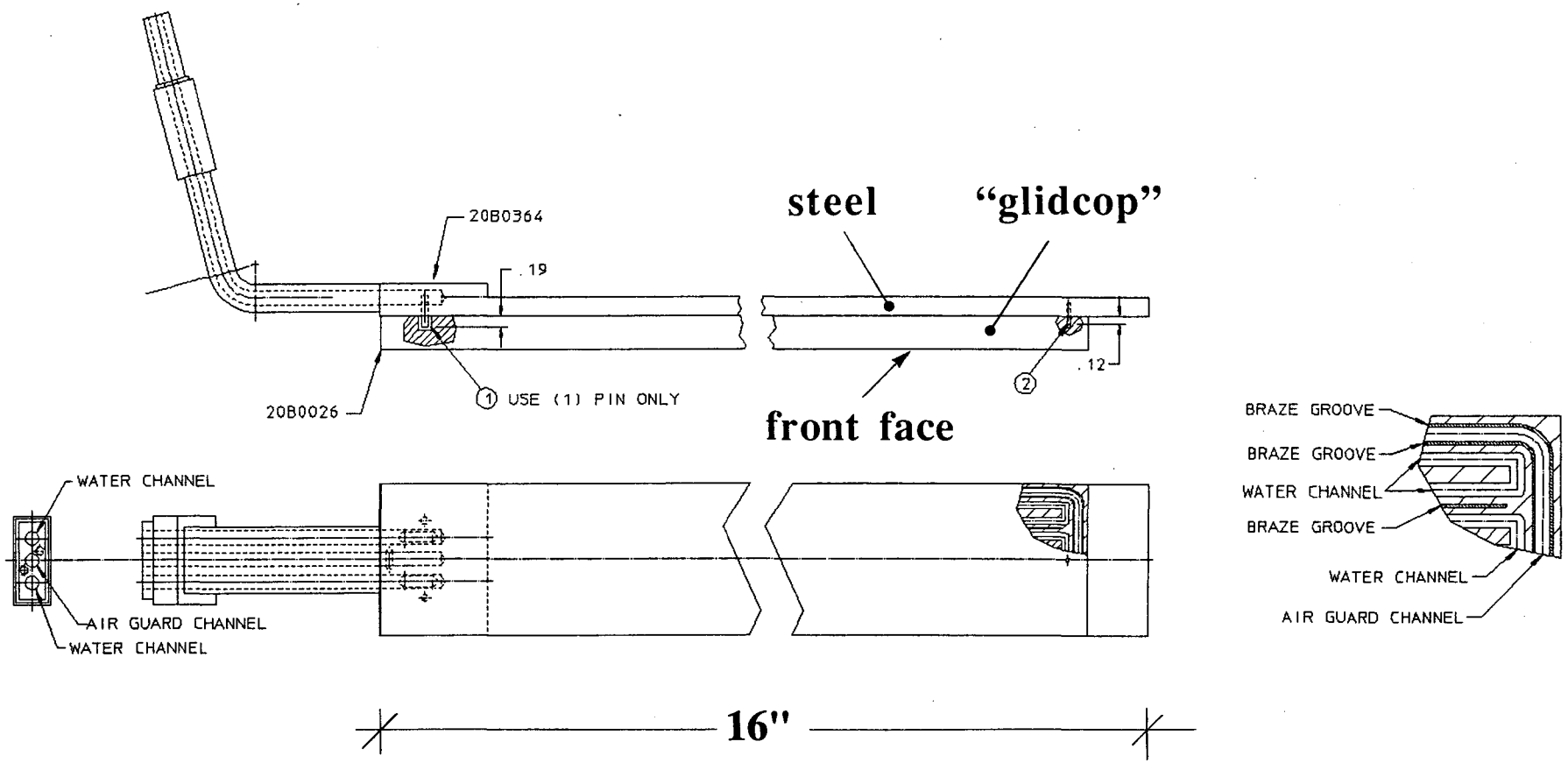


XBL-909-6738

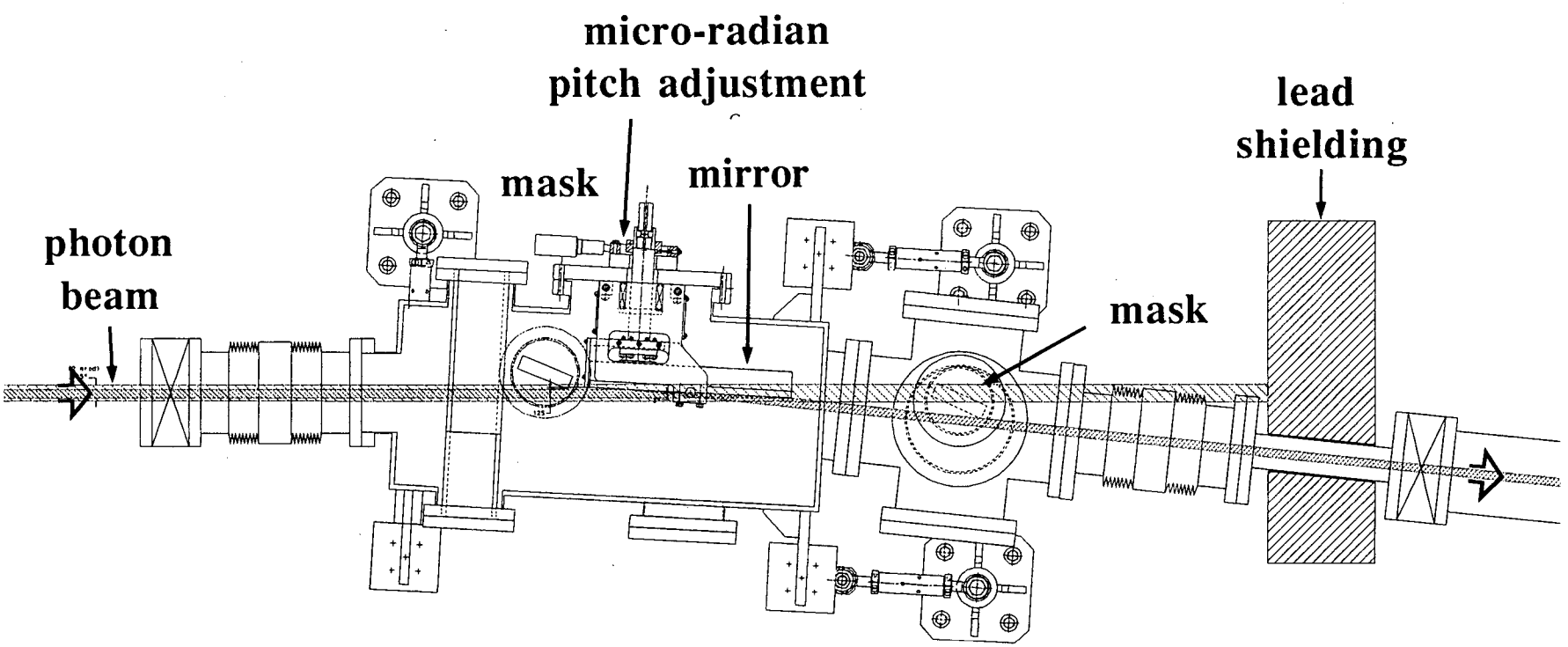
Photon shutter for undulator beams



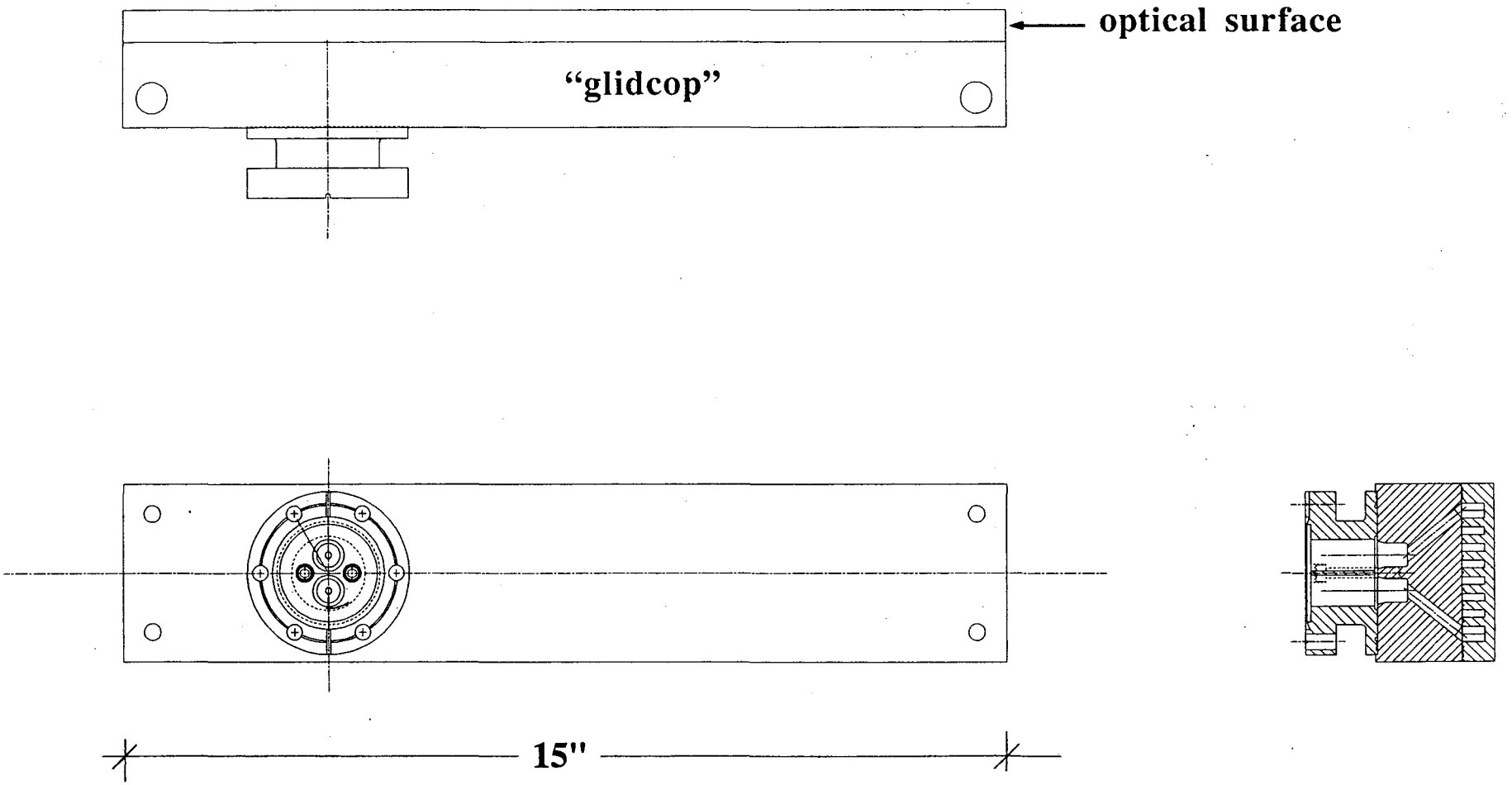
Water cooled photon shutter blade



Water cooled mirror assembly



Water cooled mirror substrate



UNDULATOR BEAMLINE COSTS (K$)

ALS

• E,D and I for 4 insertion devices	1800
E,D and I for 2 beamlines	2522
	4322

• Fabrication of 1 undulator	940
Fabrication of 1 undulator beamline,	
front end	530
branch line	1229
	2699

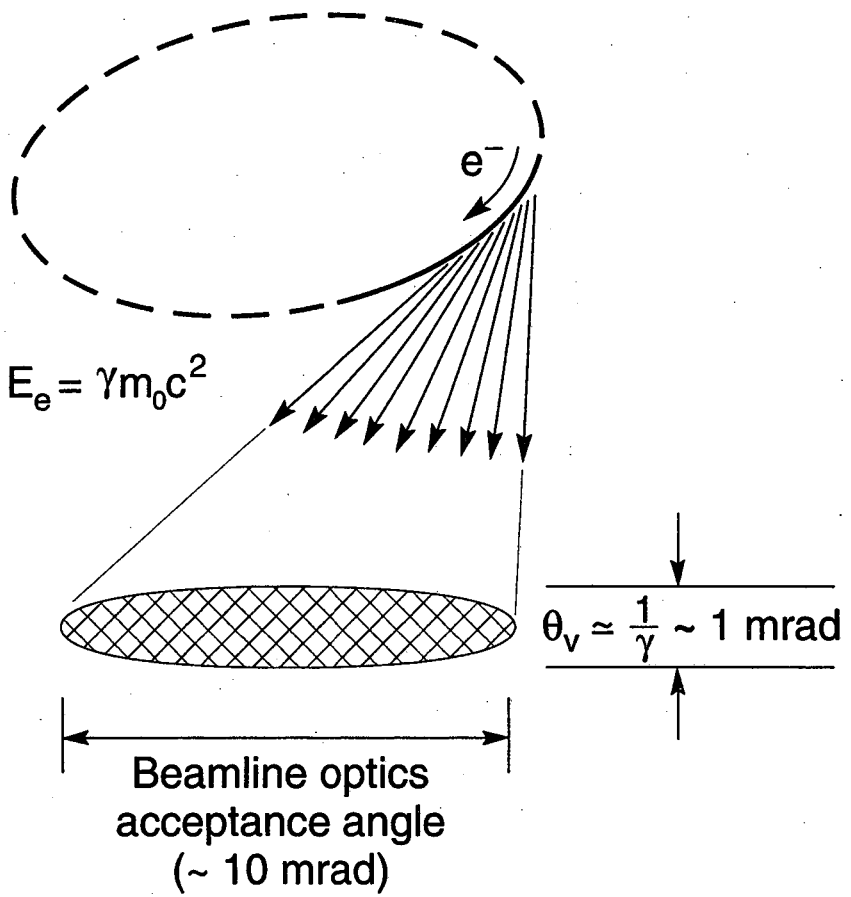
AN ALS BENDING MAGNET BEAMLINE

James Underwood

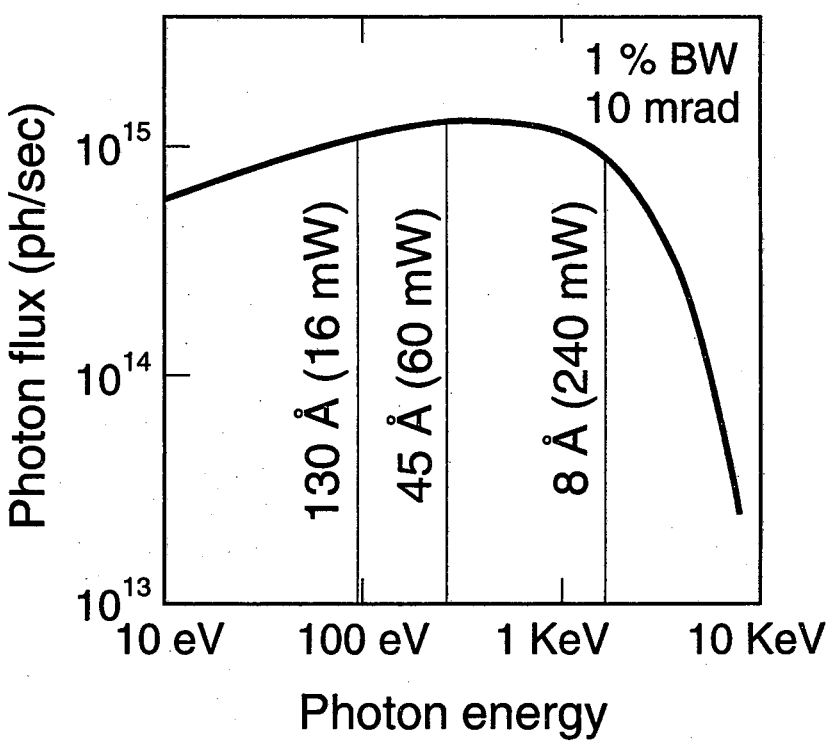
Center for X-ray Optics
Lawrence Berkeley Laboratory

Bending Magnet Radiation at the ALS

Sweeping searchlight



1.5 GeV
400 mA



XBL 911-6413

Bending Magnet Radiation and Beamlines

Advantages

- Covers a smooth, broad spectrum without magnet tuning
- Output power is relatively high
- Large angular divergence reduces thermal loading on optics
- Beamlines are less expensive (no undulator magnet structure, no water-cooled optics)

Disadvantages

- Spectral brightness is orders of magnitude less than undulator radiation

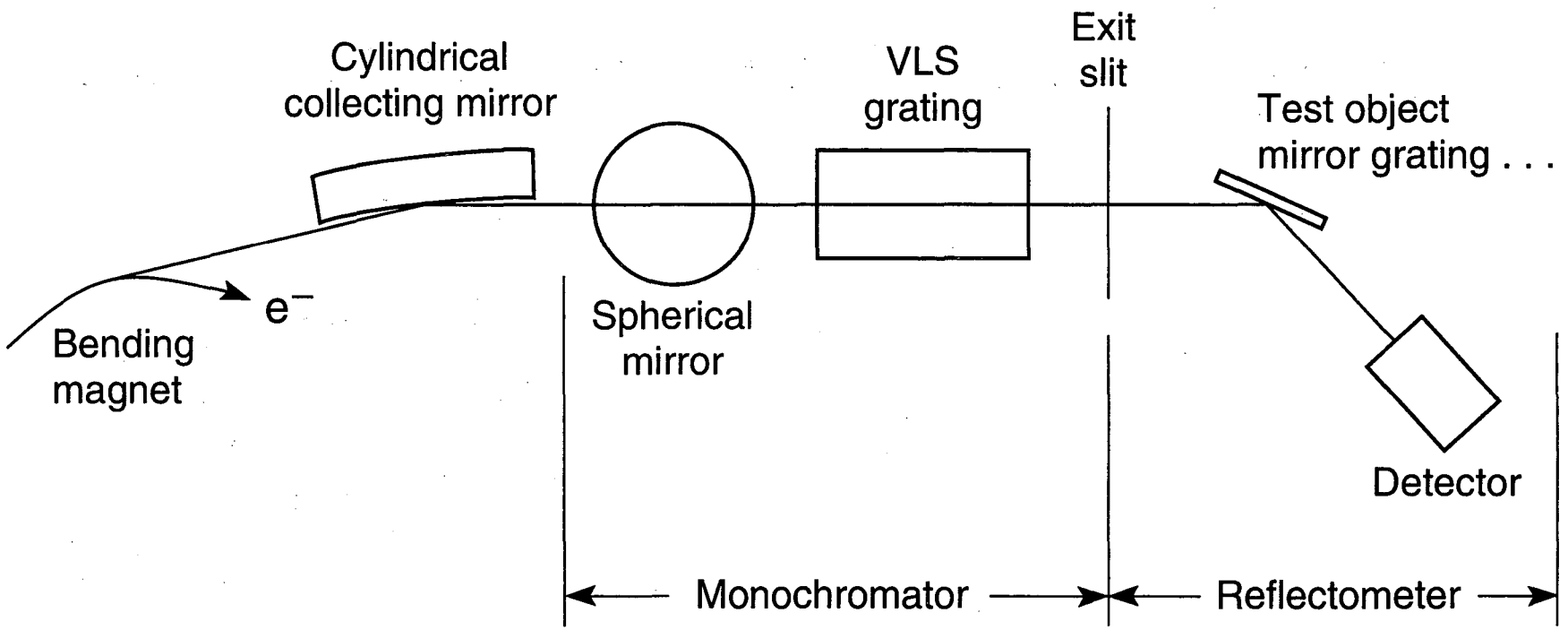
Projects That Might Benefit X-ray Lithography Using a Bending Magnet Beamline at the ALS

- Development of a soft x-ray "metrology beamline", relevant to x-ray lithography

- A relatively inexpensive facility for resist, mask, and other project research and development; readily available to university and industrial members of an appropriate consortium

- A lithography test stand for optical systems research over a broad spectral range

Schematic Diagram of Bending Magnet Beam Line



XBL 911-6415

Examples of Two Monochromators Built by CXRO

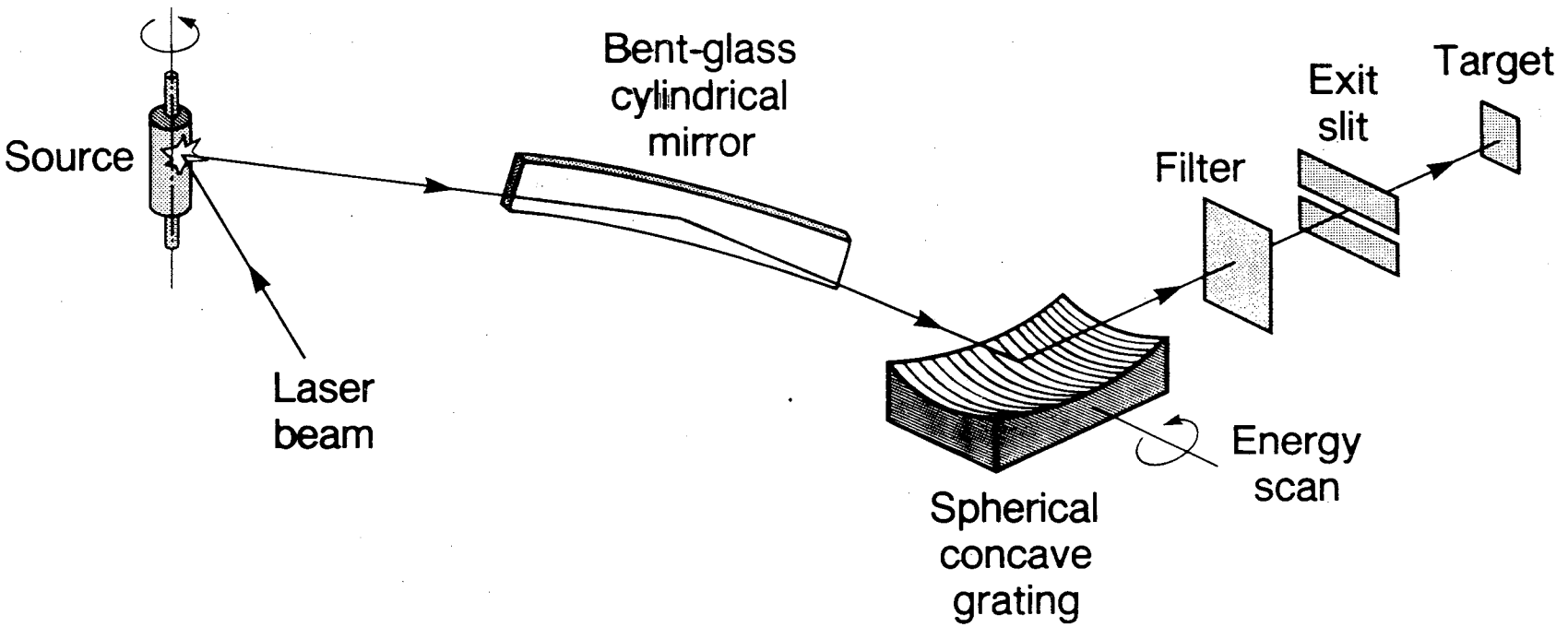
High Throughput Monochromator (HTM)

- High collection solid angle
- Simple and inexpensive
- Modest Resolution
- 30Å to 300Å spectral coverage
- Used with laser-plasma source at Sandia
- R&D-100 award

High Resolution Varied Line-Space (VLS) Grating Spectrograph

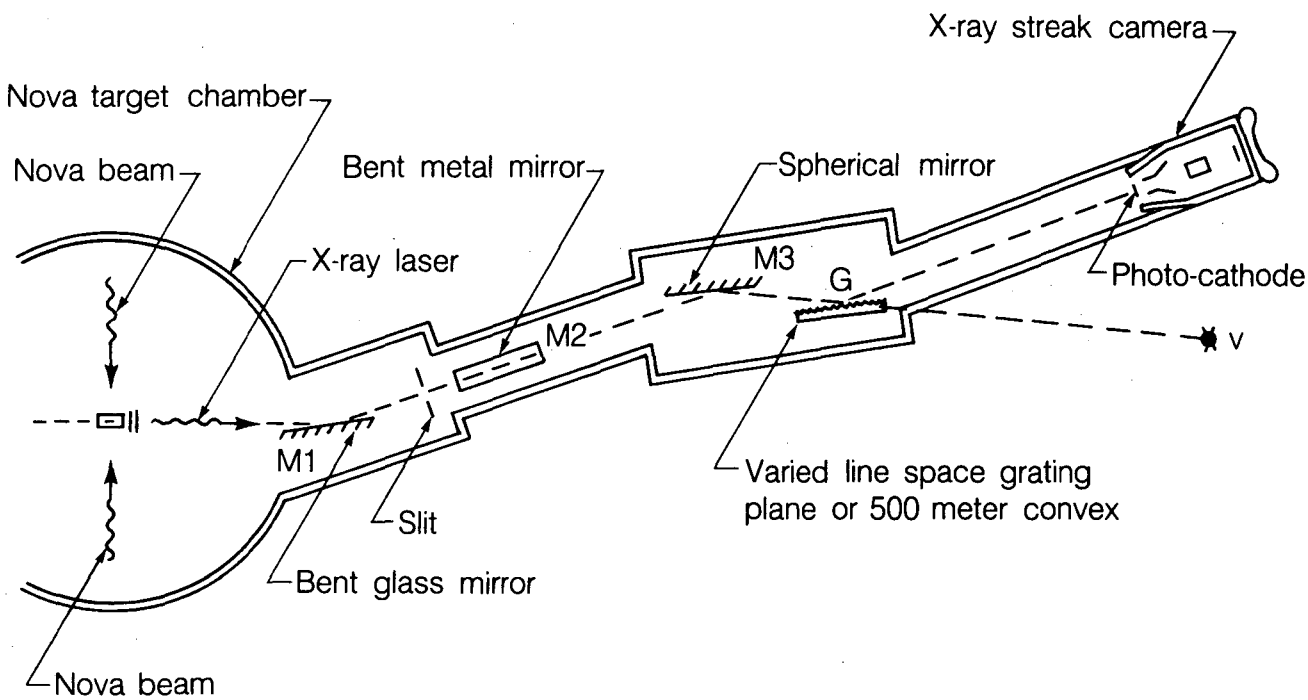
- $\frac{\lambda}{\Delta\lambda} = 35{,}000$
- 50Å to 300Å
- Simple tuning mechanism
- Best measurement of x-ray line widths at Lawrence Livermore
- R&D-100 award

Principle of High Throughput Monochromator



XBL 856-9838

High-Resolution VLS Spectrometer

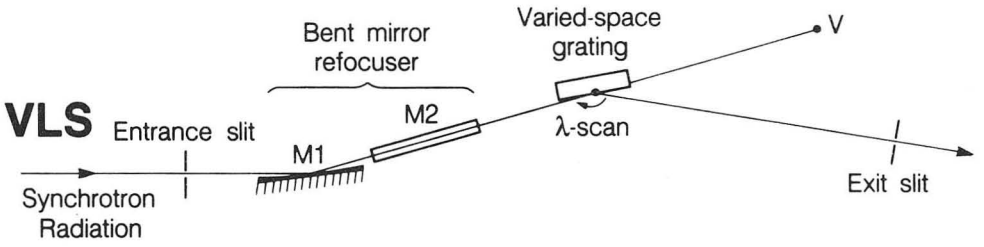


- **Spectral resolving power of 10,000 to 30,000 over wavelength band 80-250 Å; a factor of 20 higher than presently available.**
- **2-D imaging allows mapping of lasing medium.**
- **System of this type designed for measurement of LLNL x-ray laser line widths.**

XBL 866-2213

High-Resolution VLS Monochromator

- Use of elliptically or parabolically bent cylindrical pre-mirrors in combination with a VLS grating.



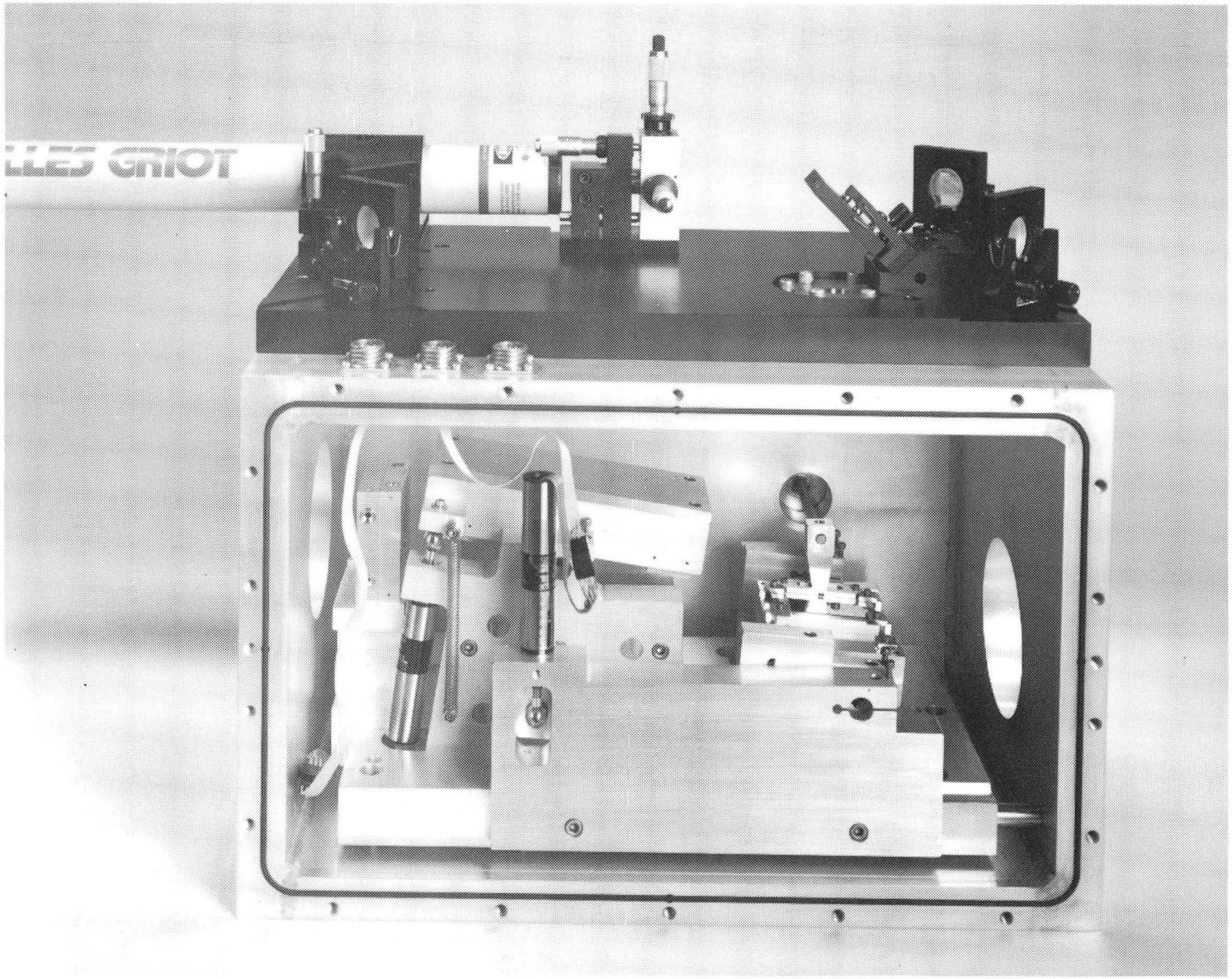
- Wavelength selection by simple rotation of grating. Conventional aberrations due to scanning in this manner, are absent.

- Removal of entrance slit permits high power loading (e.g. undulator radiation) yet retains high resolution and a physically compact instrument containing few optics.

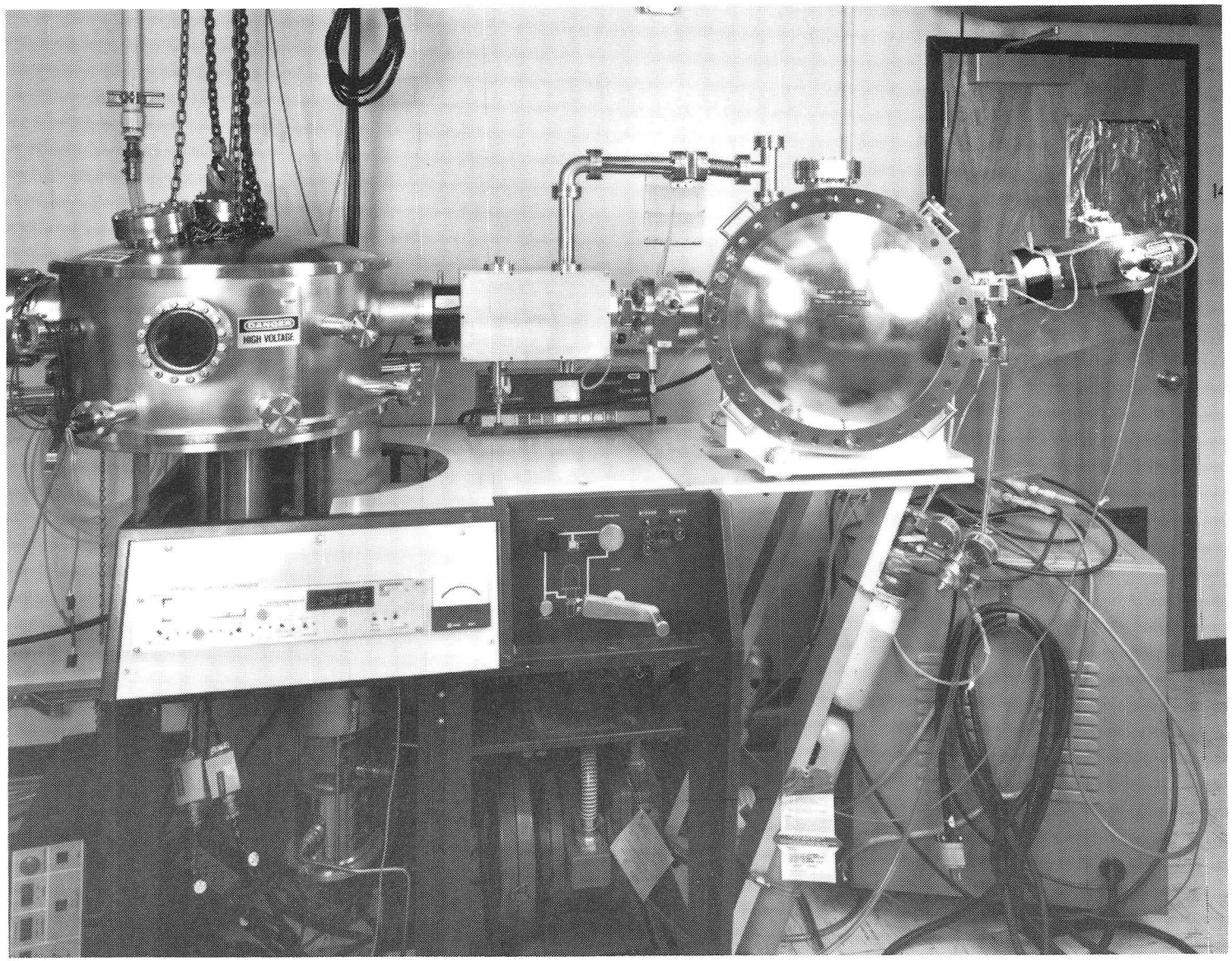
- Easily converted to flat field spectrometer with focal plane at exit slit.

XBL 866-2209

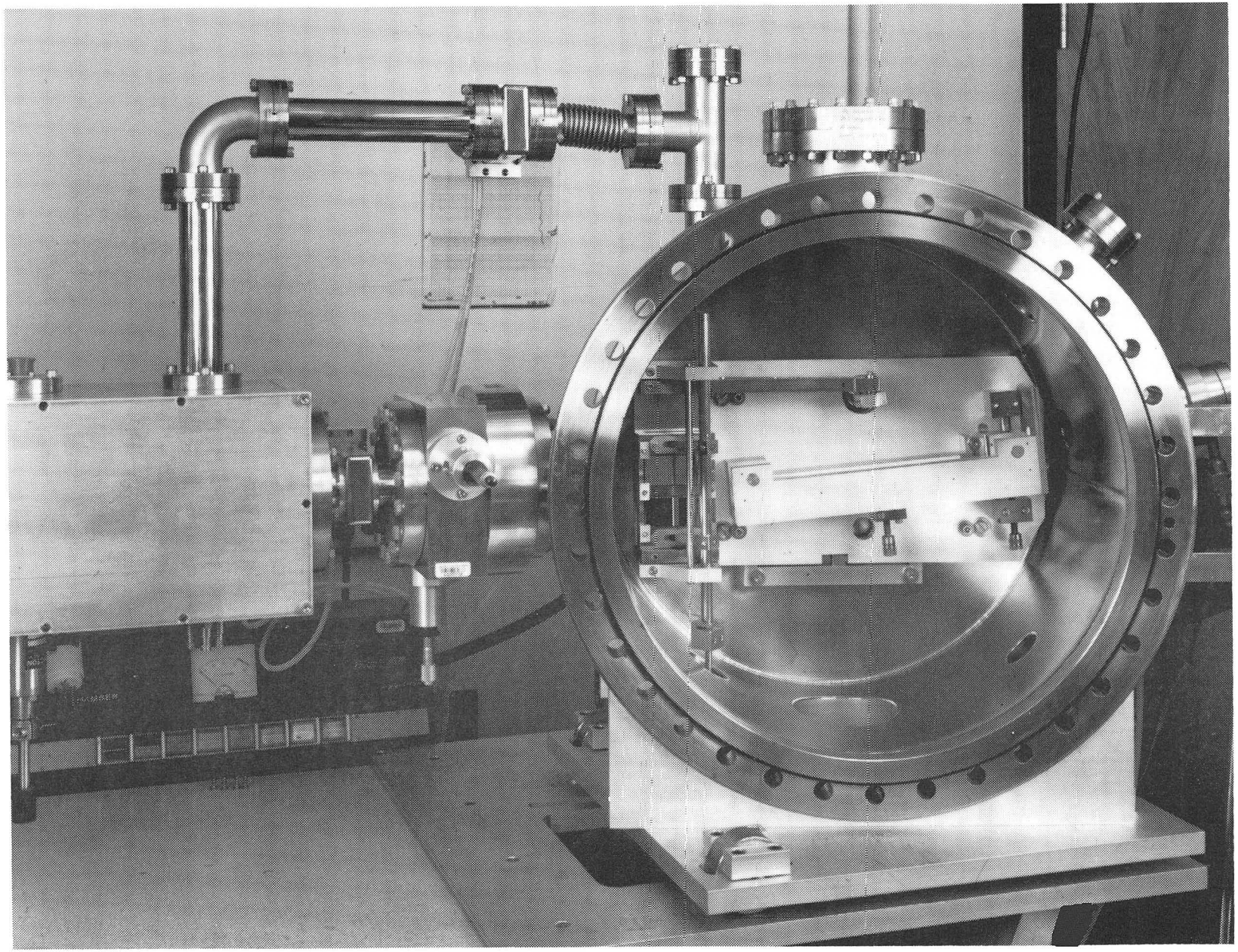
View of Interior of Special Optics Box of High Resolution VLSG Spectrograph



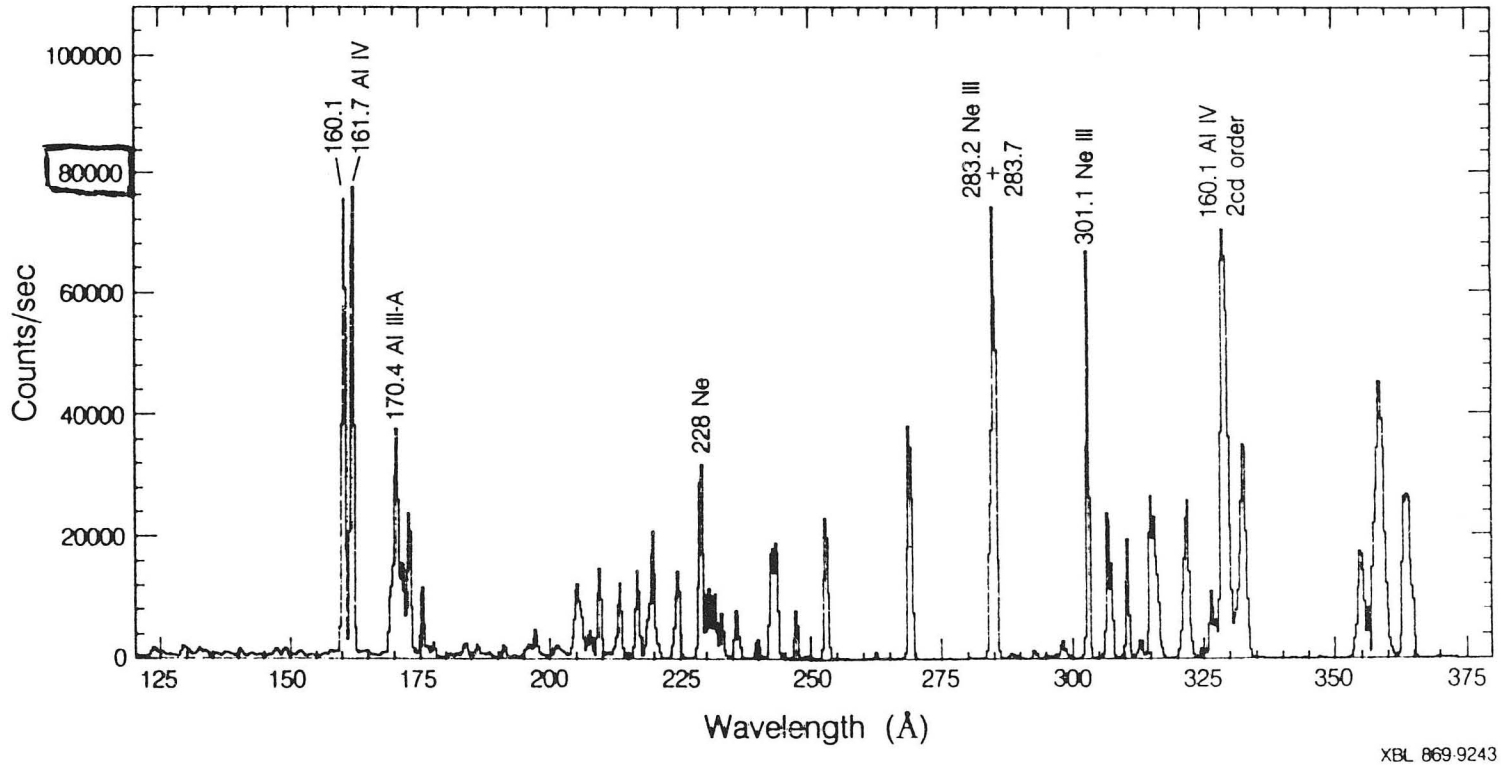
HTM Monochromator and XUV Reflectometer



View of Interior of High Throughput Monochromator

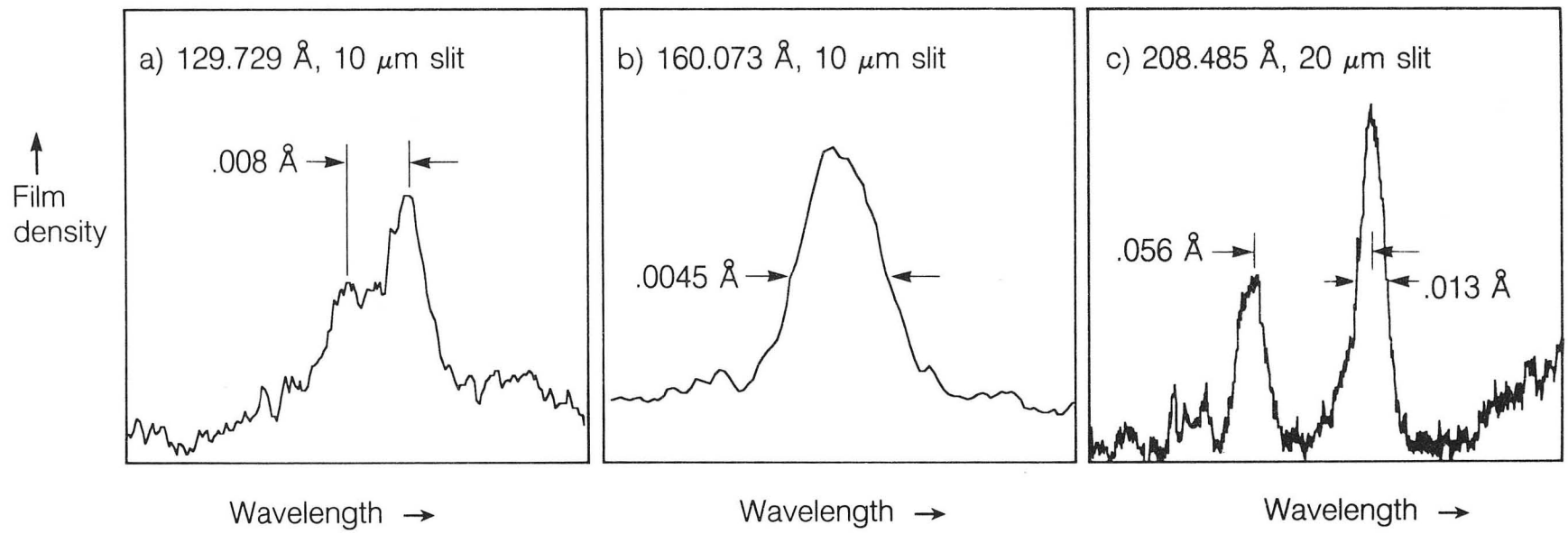


Spectrum of Ne-Al Plasma Obtained Using the High Throughput Monochromator



XBL 869-9243

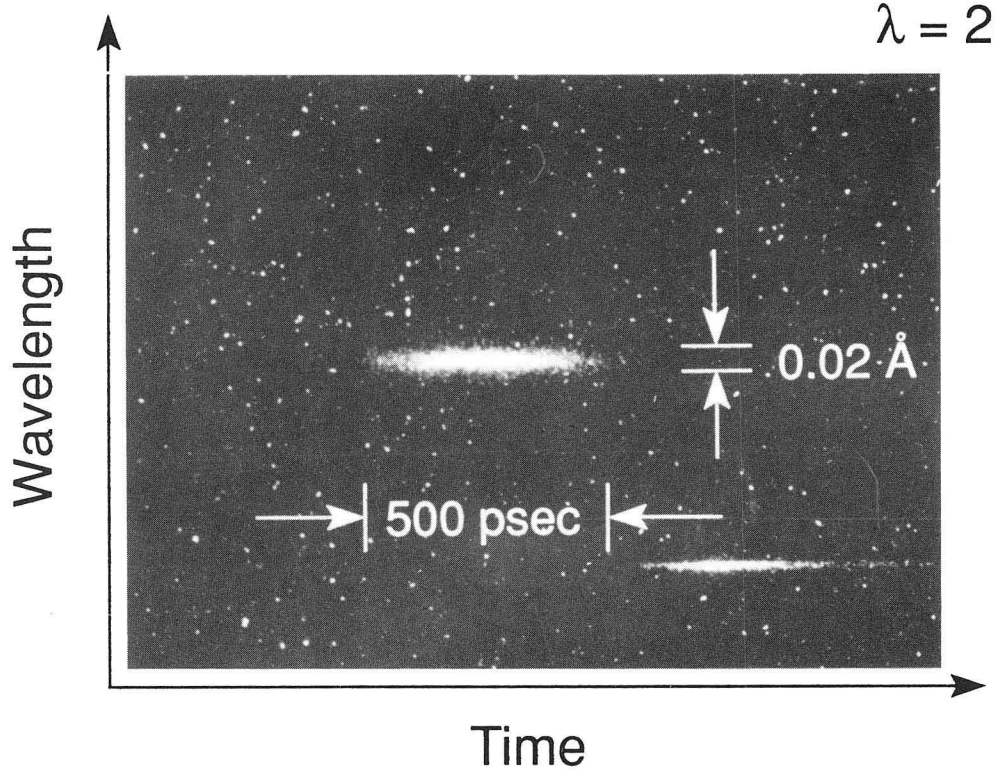
Resolution of $\lambda/\Delta\lambda$ = 35,000 Obtained With VLSG Spectrograph Using a Penning Discharge Source



XBL 879-11194

Time-Resolved X-Ray Laser Linewidth

Neon-like Selenium
$\lambda = 206.36$ Å



. . . both projects were done on time and on budget.

We are trying to organize a consortium to build a soft x-ray beam line at the ALS for the following purposes:

- Metrology and Calibration
- Development of new x-ray optics components and systems

Uses of X-ray and EUV Optics

- X-Ray and EUV Astronomy
- Plasma Diagnostics (laser fusion, etc.)
- Synchrotron Radiation Beam Steering and Focussing
- X-Ray Microscopy and Microanalysis (Biology, Metallurgy, etc.)
- X-Ray Microlithography
- X-Ray Spectroscopy
- Laboratory Calibration Apparatus (e.g. Collimators)
- Physics and Materials Research
- X-Ray Lasers

Bending Magnet Beamline Costs (K$)

Fixed Apertures	19	
Photon Shutter	61	
Fast Valve	54	
Vacuum System: Utilities & Installation	102	
Front End Safety Systems	12	
Front End Cost		249
M1 Mirror	125	
M2 Mirror	95	
M3 Mirror	64	
Monochromator (HTM)	100	
M4 Mirror	79	
Branch Line Diagnostics	63	
Vacuum System: Controls & Installation	191	
Branch Line Safety Systems	12	
Differential Pumping Sys, Optical Filters	145	
Branchline Cost		878
Engineering and Design Cost		362
Total Bending Magnet Beamline Cost		$1489K

CXRO Test and Calibration Instruments for the XUV

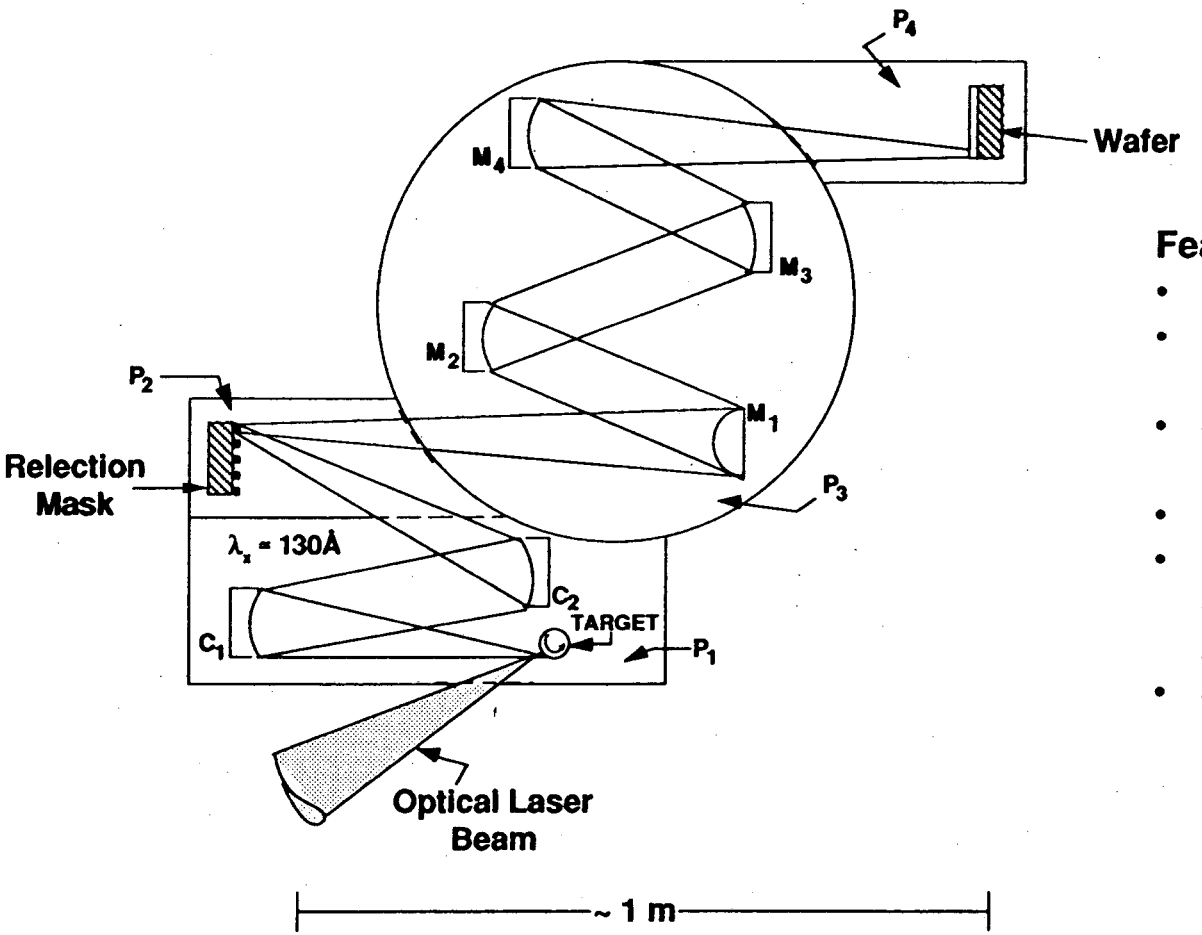
Instrument	Wavelength Range	Source	Discrete or Continuous	Source Brightness (photons/ $sec \cdot mm^2 \cdot mr^2 \cdot \%bw$	Monochromator	Use
Flat Crystal Spectrometer	2 – 114Å	Henke tube-Fluorescer	discrete lines	10^2	none	• Soft x-ray fluorescence studies • Multilayer or crystal reflectivity
Soft X-Ray Reflectometer	2 – 114Å	Henke tube	lines	5×10^5	none	• Multilayer or crystal reflectivity studies • Grating measurements
Soft X-Ray Calibration Source	2 – 114Å	Henke tube Fluorescer	lines	10^2	none	• Detector Calibrations
VUV Reflectometer	44 – 400Å	Laser-Plasma Source	Continuum or lines	10^9	High Throughput Monochromator	• Multilayer or mirror Reflectivity • Grating Characterization
2-Circle Diffractometer	CuK, CrK, MoK	tube	lines	10^7	Ge crystal	• Multilayer/Mirror Reflectivity • Crystal diffraction
4-Circle Diffractometer	CuK	Rotating Anode	lines	10^8	Ge crystal	• Multilayer/Mirror Reflectivity • Crystal diffraction

X-ray Multilayer Mirror Technology
for
Soft X-ray Projection Lithography

N. M. Ceglio
Lawrence Livermore National Laboratory

Advanced X-ray Optics Program
P.O. Box 808 M/S L-487
Livermore, CA. 94550
(415) 422-8251
fax: (415) 422-8761

SXPL: "Consensus" System Model: 1990



Features:

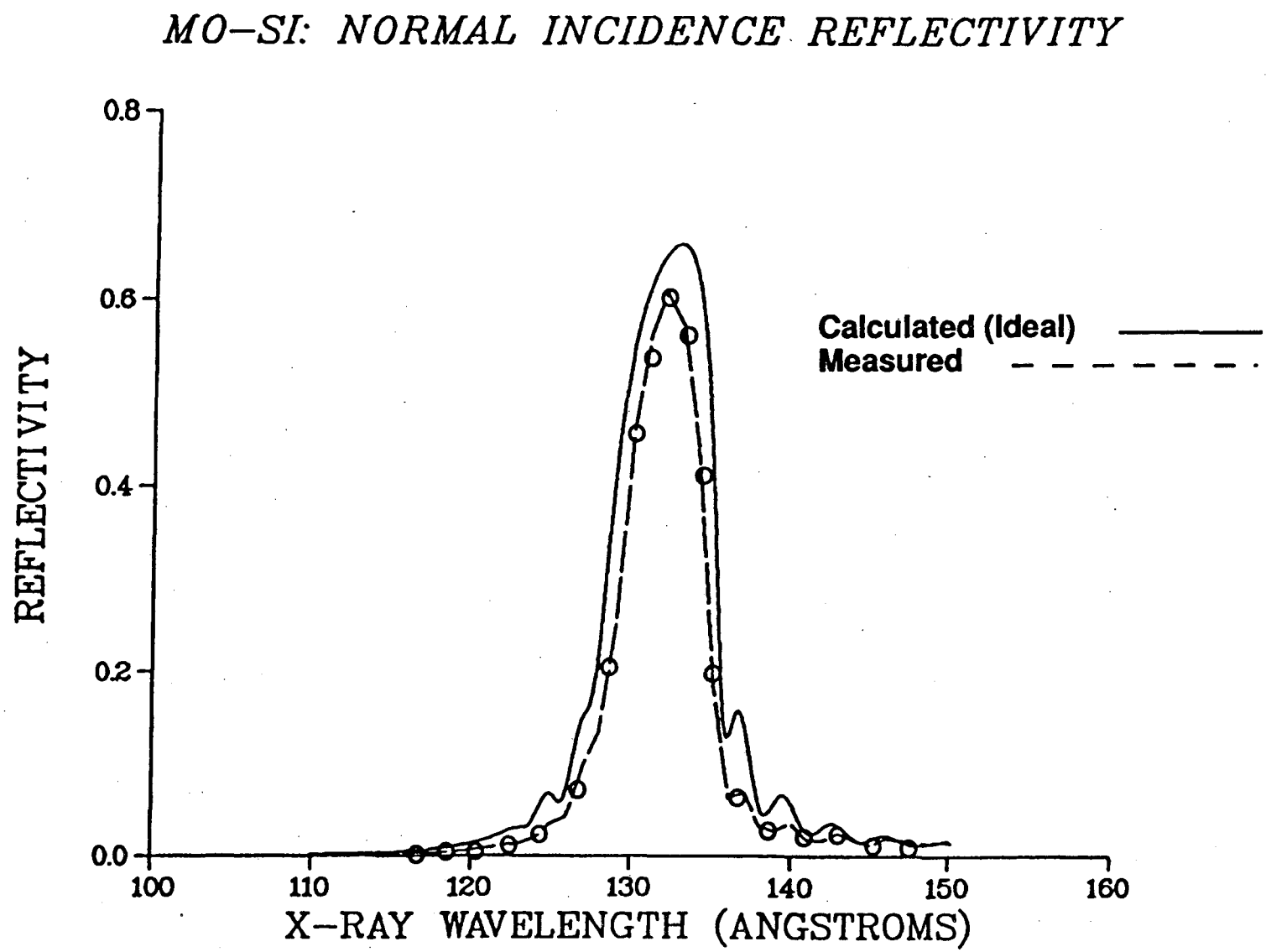
- Step and scan exposure
- X-ray source: laser produced plasma
- 4 component, precision imaging system
- X-ray reflection mask
- 7 reflecting surfaces and 3 vacuum windows between x-ray source and wafer
- 5x reduction

C_1, C_2: condenser optics
M_1, M_2, M_3, M_4: imaging optics
P_1, P_2, P_3, P_4: four different vacuum environments

Multilayer Technology Development: Critical Issues for SXPL

Multilayer Technology		
High Reflectivity Multilayers	Precision Deposition on Figured Surfaces	Multilayer Damage/ Repair
"R" is the most critical parameter determining system performance $T \alpha R^7$ $T_{max}(R)$	Unprecedented deposition requirements (Infant Technology) Need unique characterization Capabilities & Experience	Vital to economic viability

Mo/Si Multilayer Mirror Performance @ λ ~ 130Å



Precision Multilayer Deposition on Figured Surfaces:

Work in Progress

- New facility for precision coating large (≤ 4" diameter), curved mirrors
- New facility (unique) for characterizing coatings on curved mirrors
  - 200μm spot size
  - R (x,y) over mirror surface
  - Can measure diameter ≤ 4"
  - Can measure focal length ≥ 6 cm

Technical Issues in SXPL: Need for Survivable or Repairable Multilayer Coatings (System Cost Analysis)

The Precision Imaging Optics in a SXPL system are likely to be a significant cost item (0.25 M$ - 0.5 M$).

The need to keep C_E under control requires:

- Multilayer coatings on precision optics must be able to survive the x-ray lithography environment (i.e. lifetime ~ years)

– or –

- Techniques be developed to strip and recoat the multilayers without damaging the precision substrate surface.

X-RAY LITHOGRAPHY AT IBM

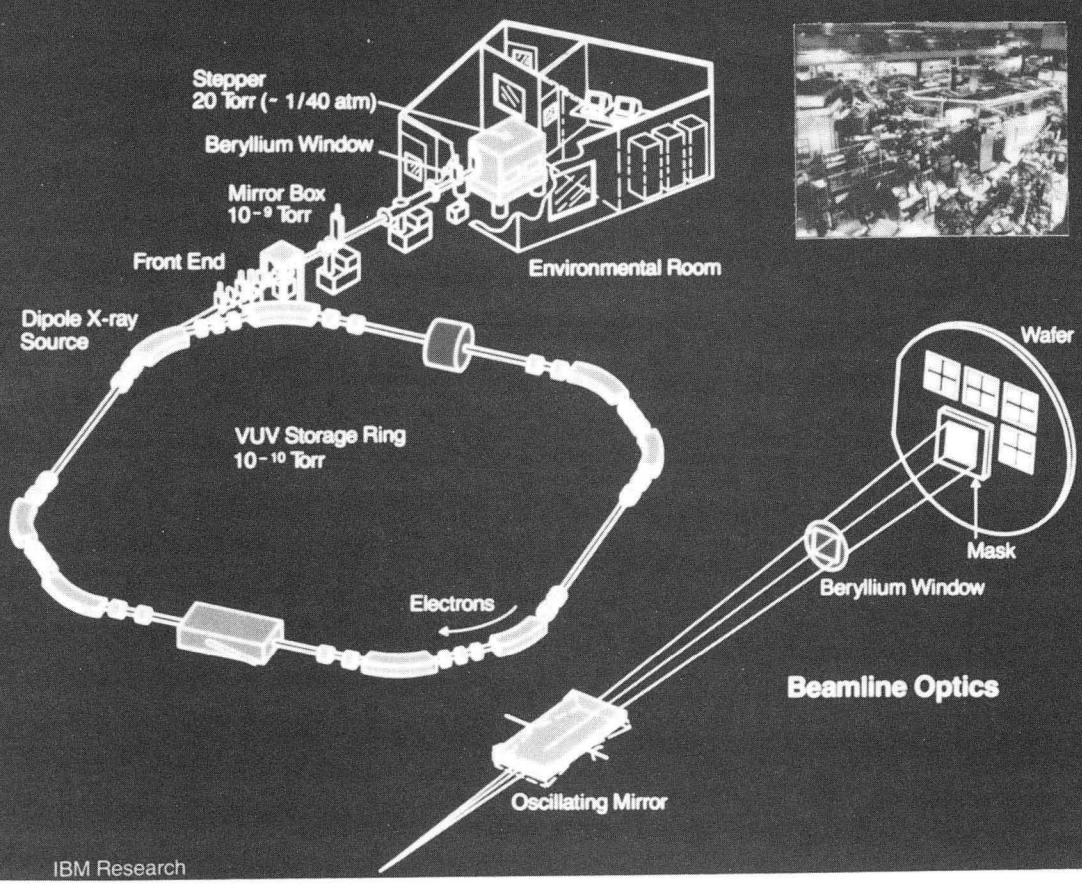
John Warlaumont

Thomas J. Watson Research Center, IBM

Brookhaven Facility

- National Synchrotron Light Source, VUV ring, port U6
- Circulating electron beam radiates intense flux of ~ 10 Å x-rays (10 mW/cm^2 on wafer)
- Small source size produces negligible penumbral blur
- Uniform mask illumination by scanning mirror

IBM Lithography Facility

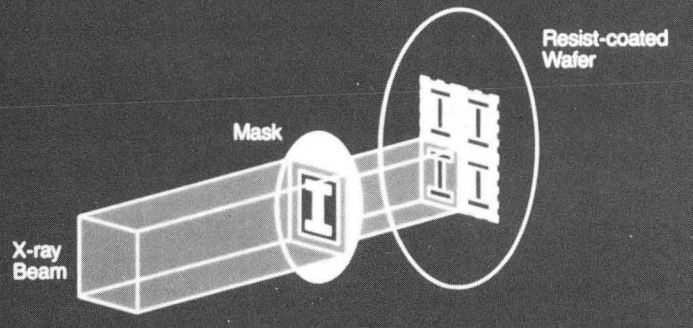


IBM Research

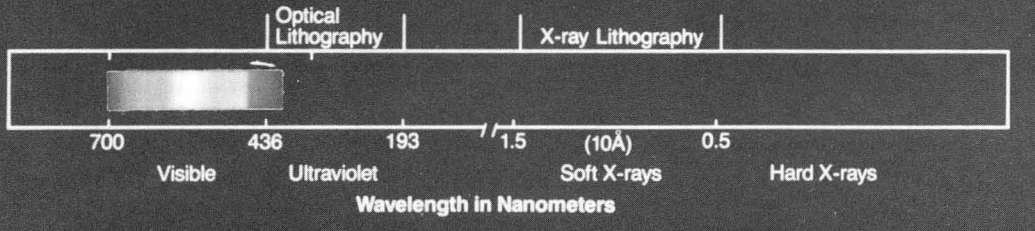
X-ray Shadow Printing

- High throughput parallel printing process
- Large field size (no lens)
- Resolution ≃ 0.1 μm (1000 Å) with very **high aspect** ratios
- Insensitive to many common particulate defects

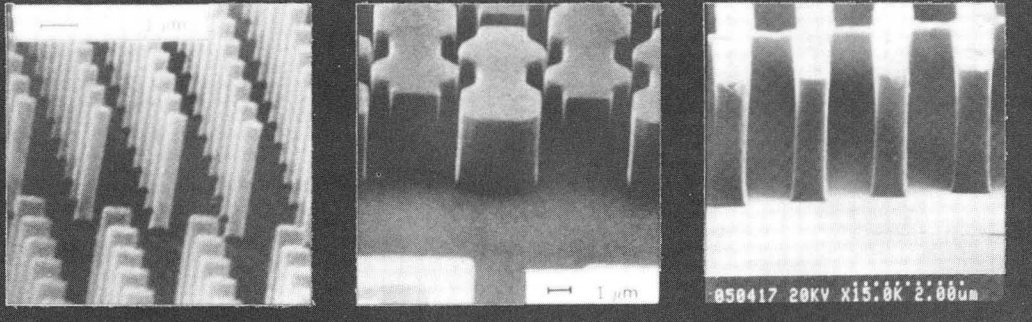
Printing Principle



Photon Spectrum



High Aspect Ratio Resist Images

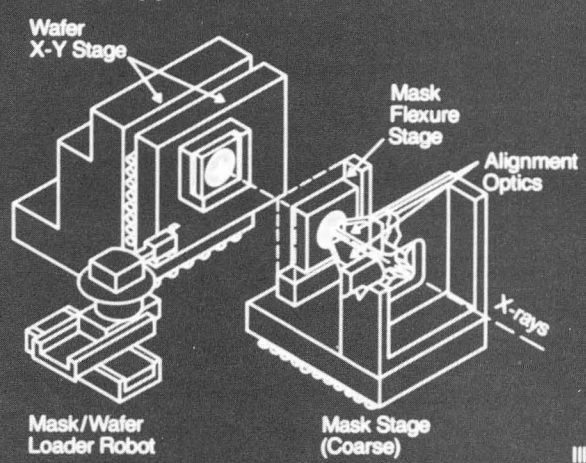


IBM Research

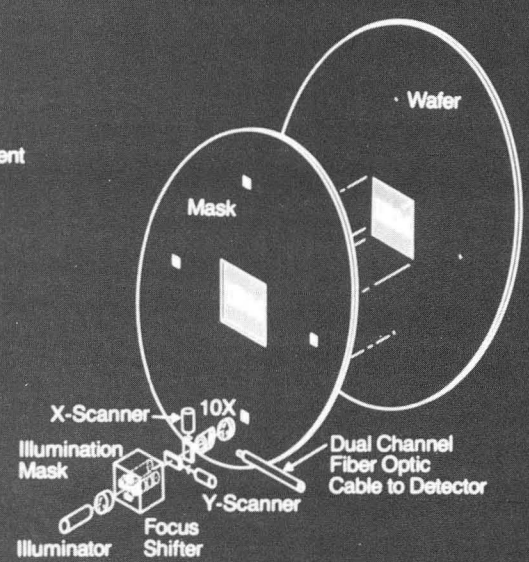
Mask/Wafer Aligner

- Scanning dark-field alignment technique
- Step and repeat on wafer

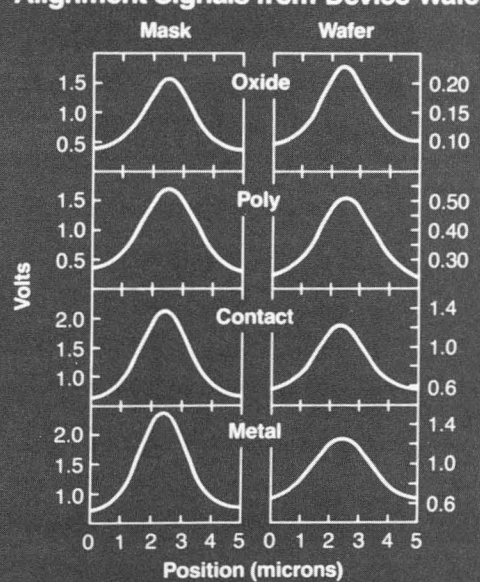
X-ray Stepper



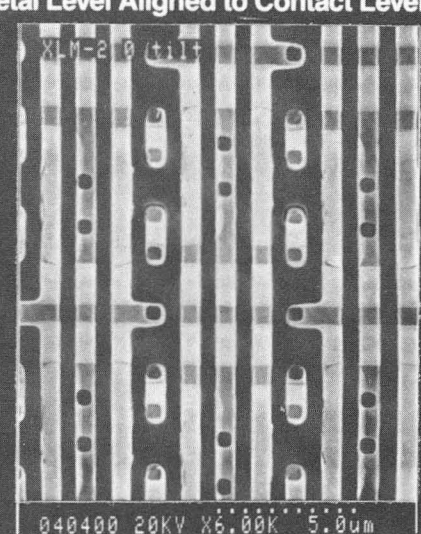
Alignment System



Alignment Signals from Device Wafers



Metal Level Aligned to Contact Level

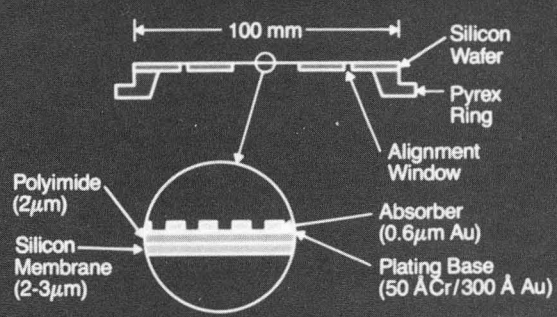


IBM Research

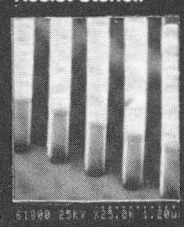
X-ray Mask

- Masks patterned by vector-scan e-beam lithography
- Linewidth control 0.02 μm (1σ) for 0.5 μm features
- Mask-mask overlay 0.03 μm (1σ) measured with optical metrology tool

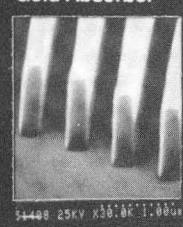
Mask Structure



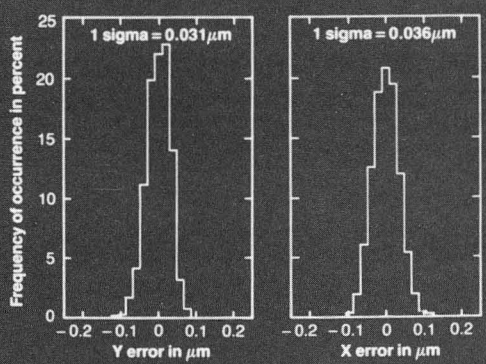
Resist Stencil



Gold Absorber



CMOS Device Masks Overlay to ROX Level

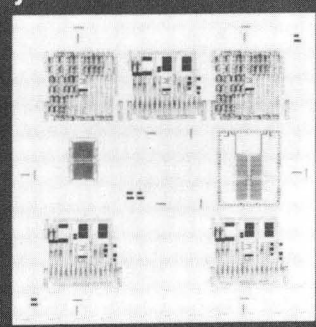


Mask Layout

Test Circuits

64K SRAMs

Test Circuits



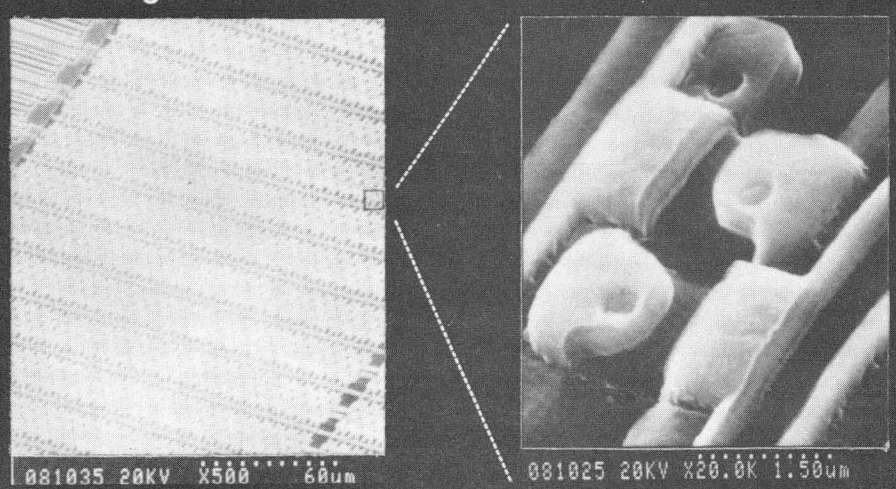
Patterned area 25 × 25 mm^2

IBM Research

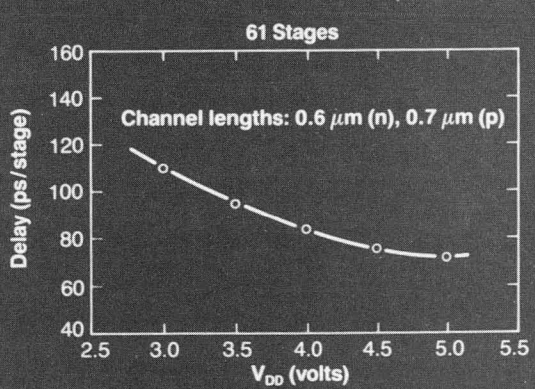
0.5 μm CMOS Circuits

- 8 levels, all by x-ray lithography
- Fully-scaled 0.5 μm ground rules
- Functional transistors and ring oscillators
- All x-ray exposures done at Brookhaven National Laboratory

SRAM Integrated Circuit



CMOS Ring Oscillators

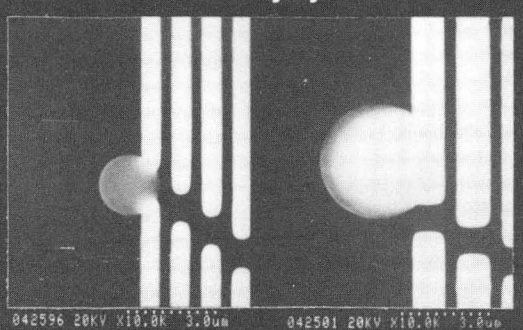


IBM Research

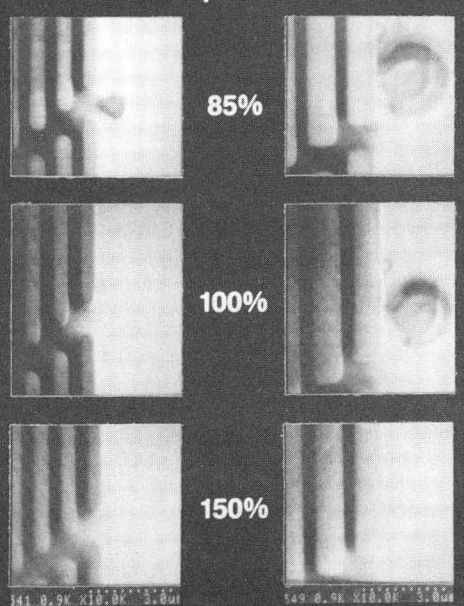
Defect Insensitivity

- Low atomic number (Z) particles (Si, C, Al, ...) weakly absorb 1 nm (10Å) x-rays ($\simeq 10\%/\mu m$)
- Micron-size low Z particles don't print
- Mask features (high Z) still have high fidelity images
- Demonstrated by intentionally adding defects to mask

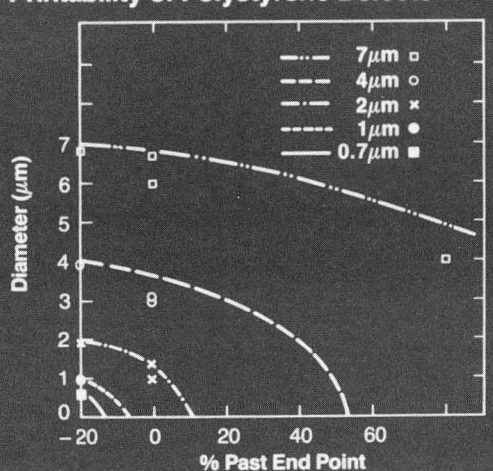
Mask with Added Polystyrene Defect



X-ray Print of Mask with Defect at Three Development Points



Printability of Polystyrene Defects

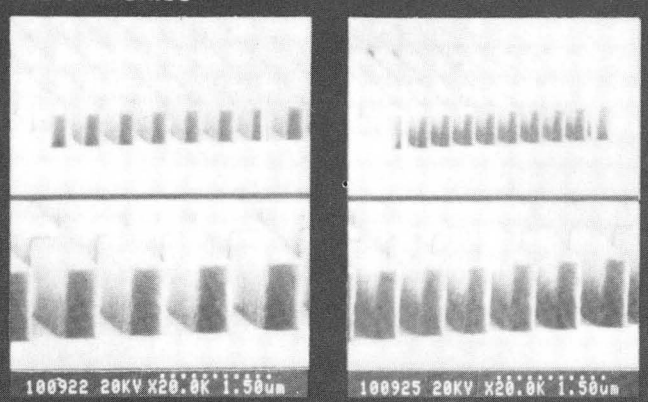


IBM Research

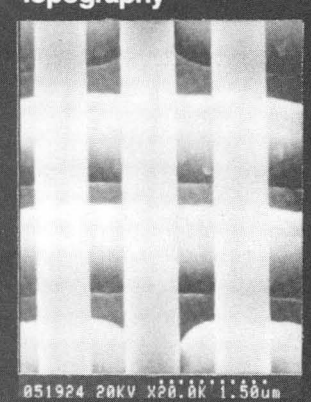
Single-Layer Resists

- Novolak positive resists 1-2 μm thick
- Same resist is used in IBM manufacturing for optical lithography
- Single-layer (1-3 μm) negative resists also used

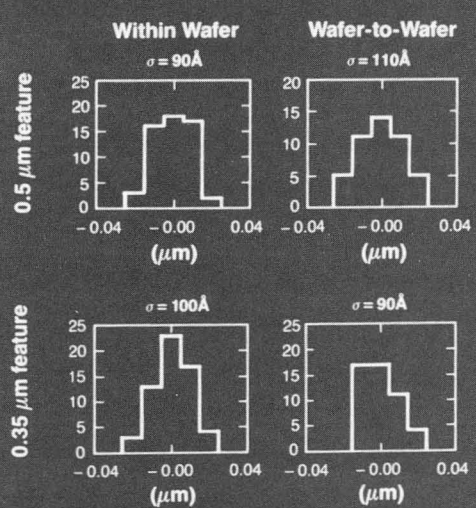
Resist Profiles



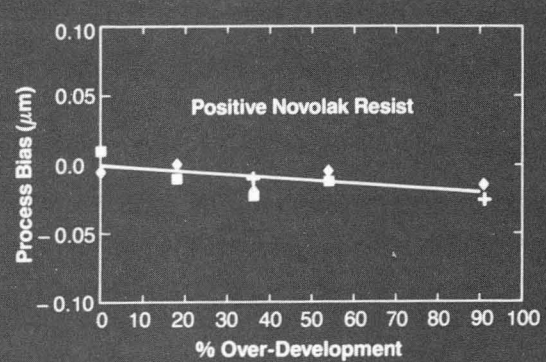
Resist over Device Topography



Linewidth Control Field-to-Field



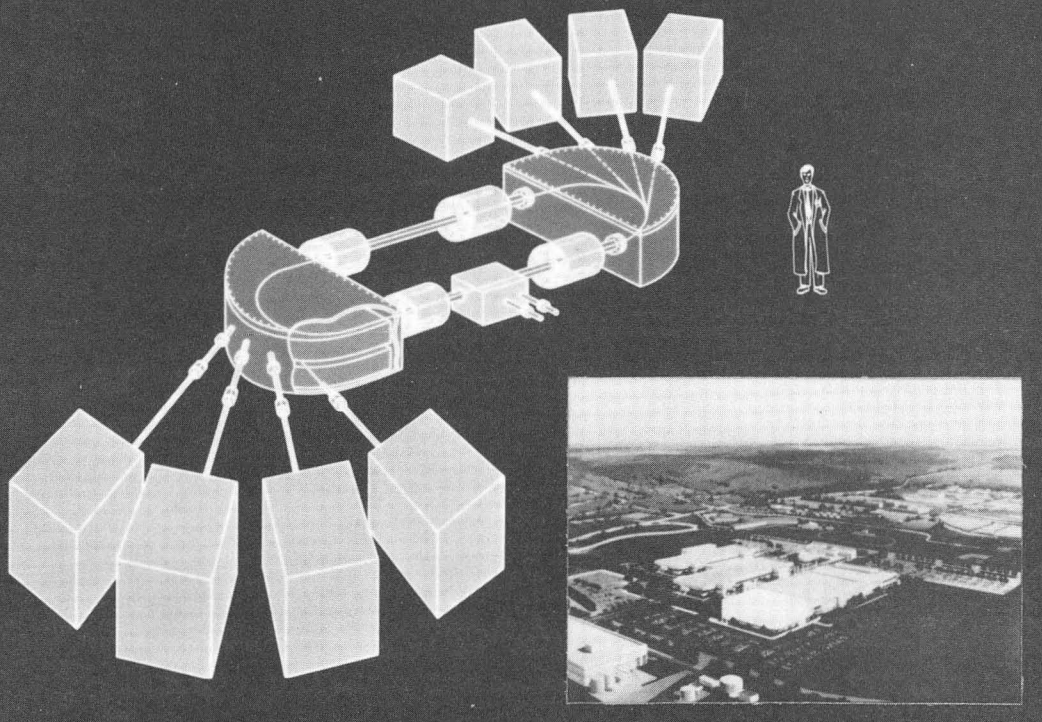
Linewidth Change with Over-Development



IBM Research

Future

- Compact electron storage ring at East Fishkill advanced lithography facility (100 mW/cm^2 on wafer)
- 0.1 μm x-ray mask patterning by high voltage (100 keV) vector scan
- 0.1 μm ground rules mask/wafer aligner, at atmospheric pressure
- Mask repair using focused ion beams



IBM Research/GTD

PROJECTION LITHOGRAPHY USING SOFT X-RAYS

John Bjorkholm

J. Bokor
L. Eichner
R. R. Freeman
T. E. Jewell
W. M. Mansfield
A. A. MacDowell
L. H. Szeto
D. M. Tennant
W. K. Waskiewicz
D. L. White
D. L. Windt
O. R. Wood, II

AT&T Bell Laboratories

Outline

- Why projection lithography?

- Small image field systems and undulator radiation.

  Schwarzschild 20:1
  Offner 1:1

- Future large image field systems, bending magnet radiation.

  Aspheres — high precision.

- Optical testing — undulators.

Why X-ray Projection Lithography?

- High resolution with reasonable DOF.
- Easier mask fabrication with reduction.

What we aim for:

$$\text{resolution} = \frac{\lambda}{2\,\text{NA}} \leq 0.1\ \mu\text{m}$$

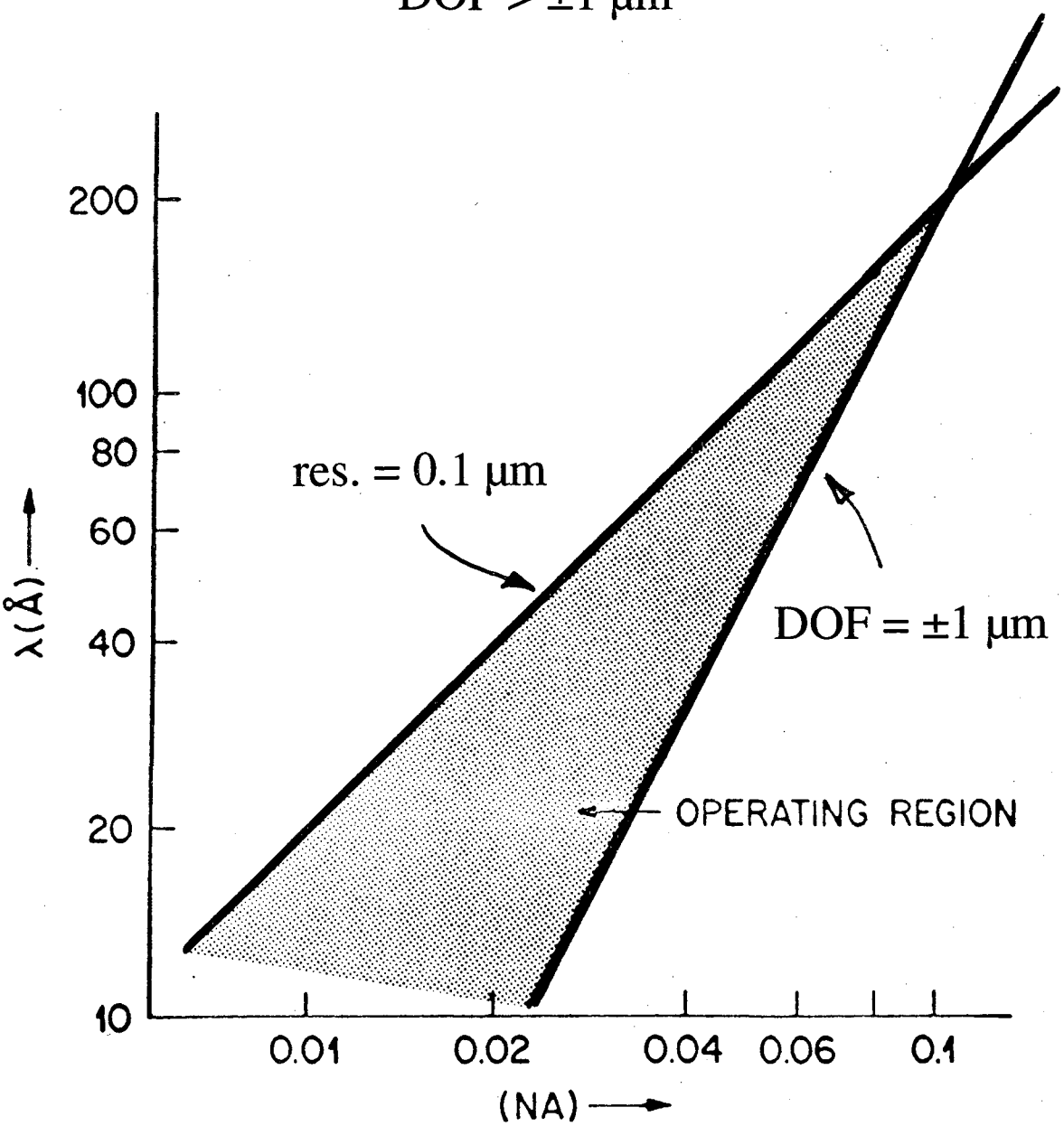
$$\text{DOF} = \pm\ \frac{\lambda}{2\,(\text{NA})^2} \geq \pm\ 1\ \mu\text{m}$$

What is required?

Imaging Requirements for:

resolution < 0.1 μm

DOF > ±1 μm



Problems: Properties of materials; Optics

Materials are highly absorbing — must use mirrors.

- Very poor reflectance for $\lambda < 40$ nm.
- Multilayer mirrors for 13 nm $< \lambda <$ 30 nm.

$\therefore$ Vacuum process; resists are very absorbing.

Mirror Optics:

— Systems more difficult than with lenses.

— Aspheres.

— Stringent requirements on surface figure and surface roughness.

Small Field Imaging

U13 undulator at NSLS.

Good features:

Small beam size matches mask size — no illumination optics needed.

Good power.

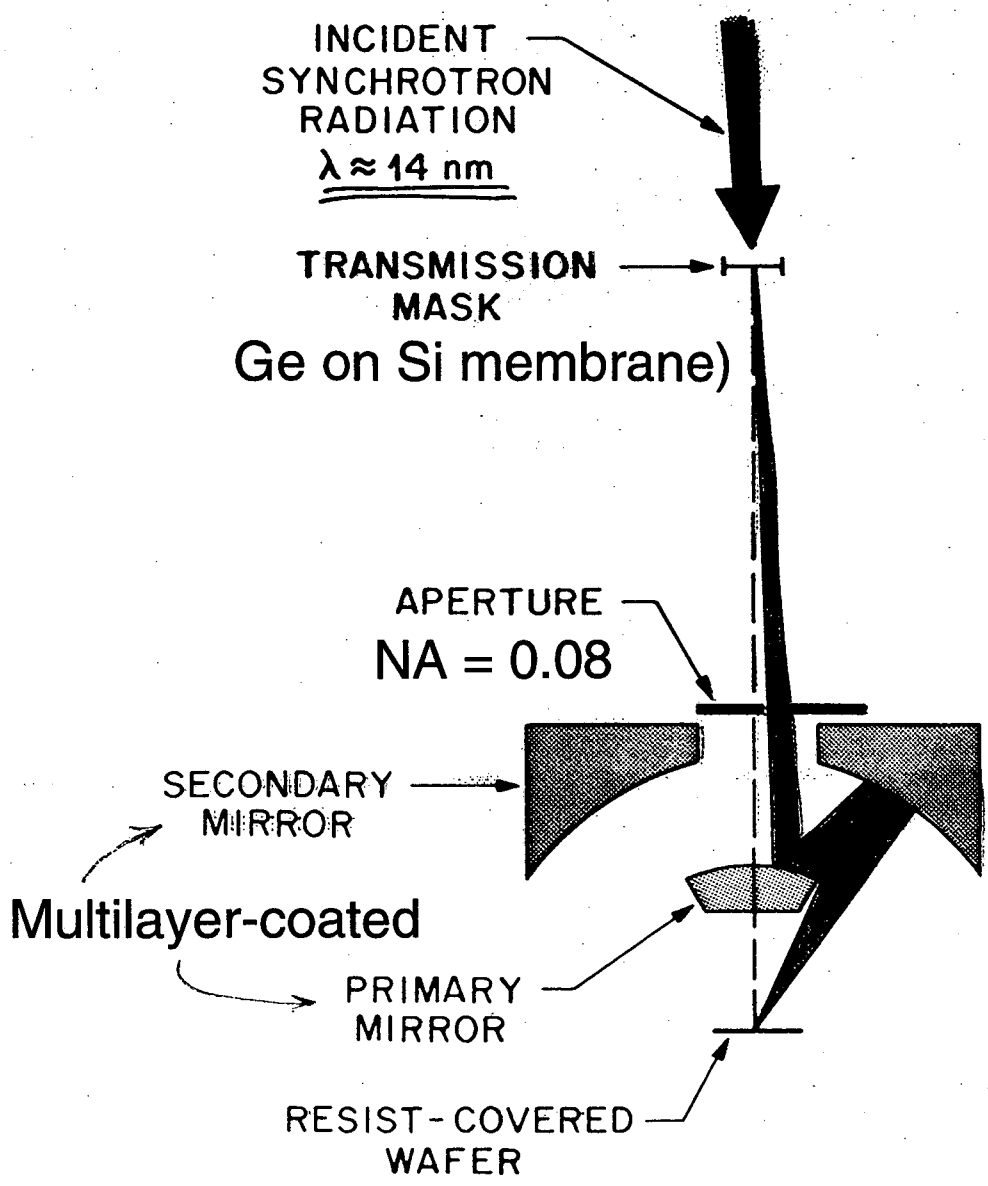
Small spectral bandwidth — good match to BW of multilayers.

Bad Features:

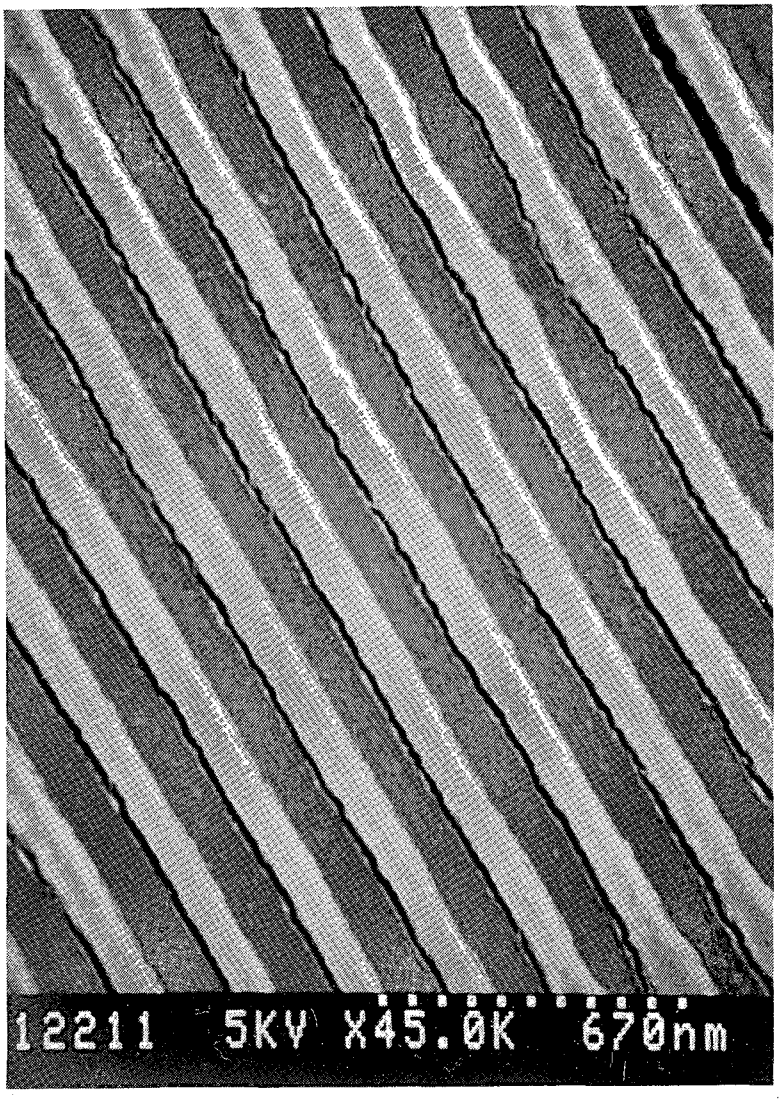
Spatial coherence — leads to "coherence ringing".

Schwarzschild Objective

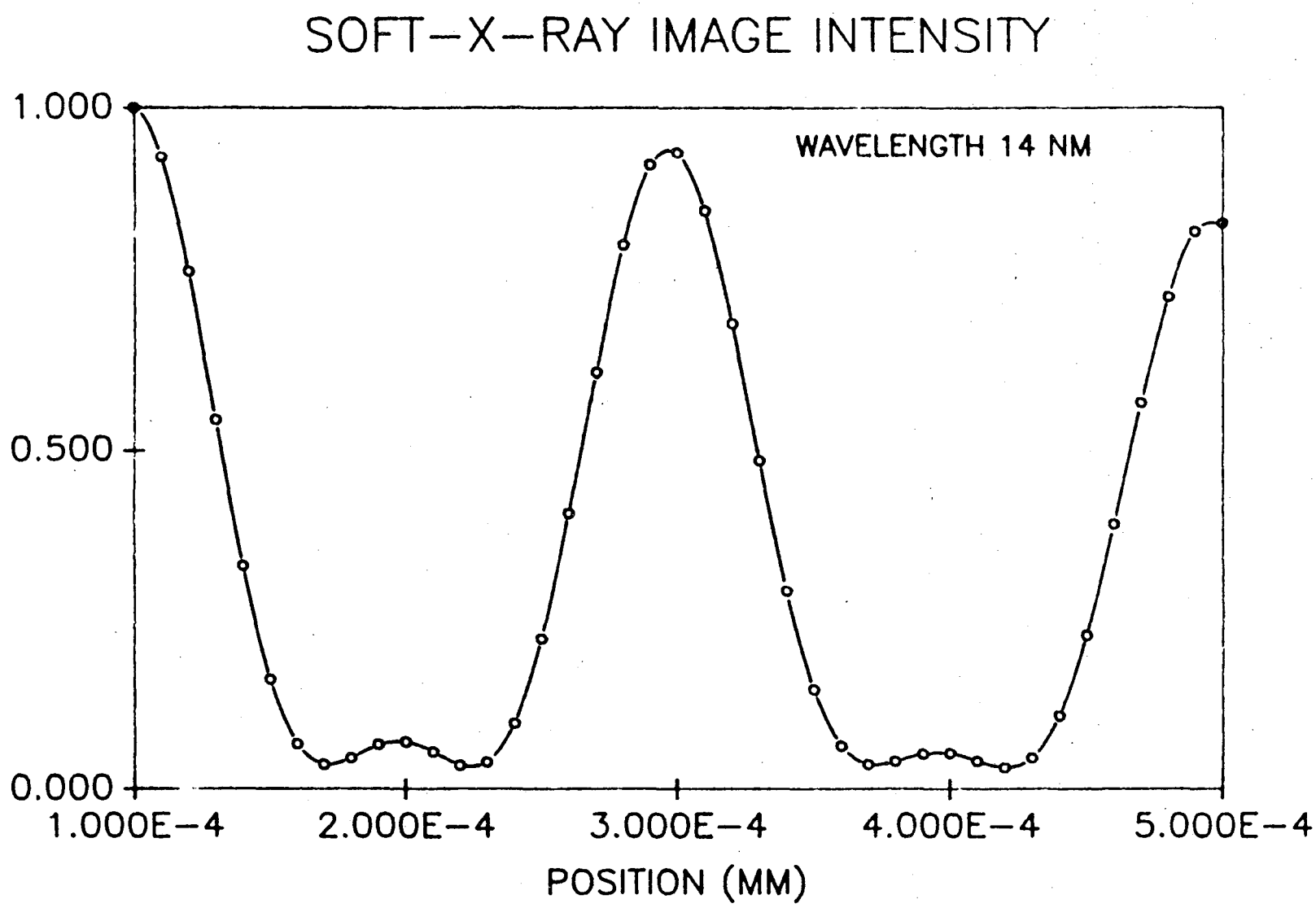
20:1 reduction
multilayer-coated mirrors (Mo:Si)

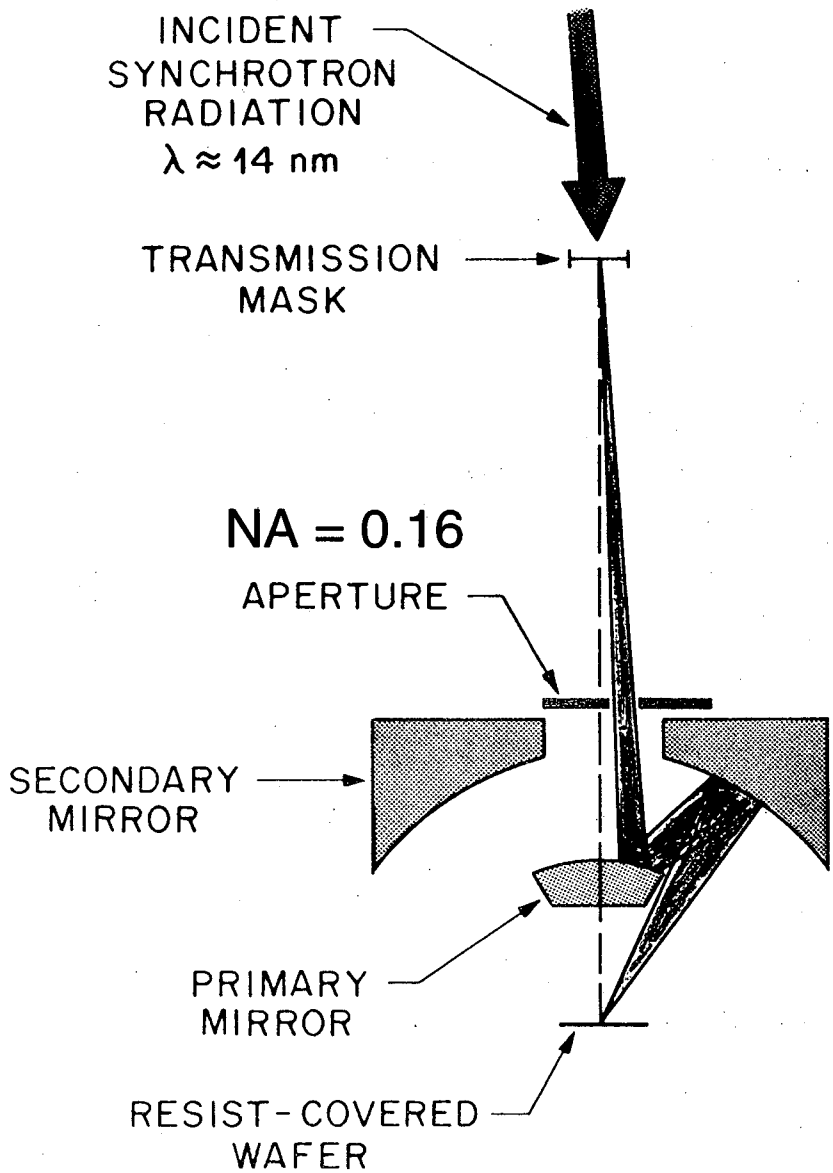


res. ≈ 0.09 μm DOF ≈ ± 1.1 μm



0.1 μm lines and spaces in PMMA (60 nm thick).
Exposed using 20:1 reduction Schwarzschild
with multilayer coated mirrors and radiation at 14 nm.

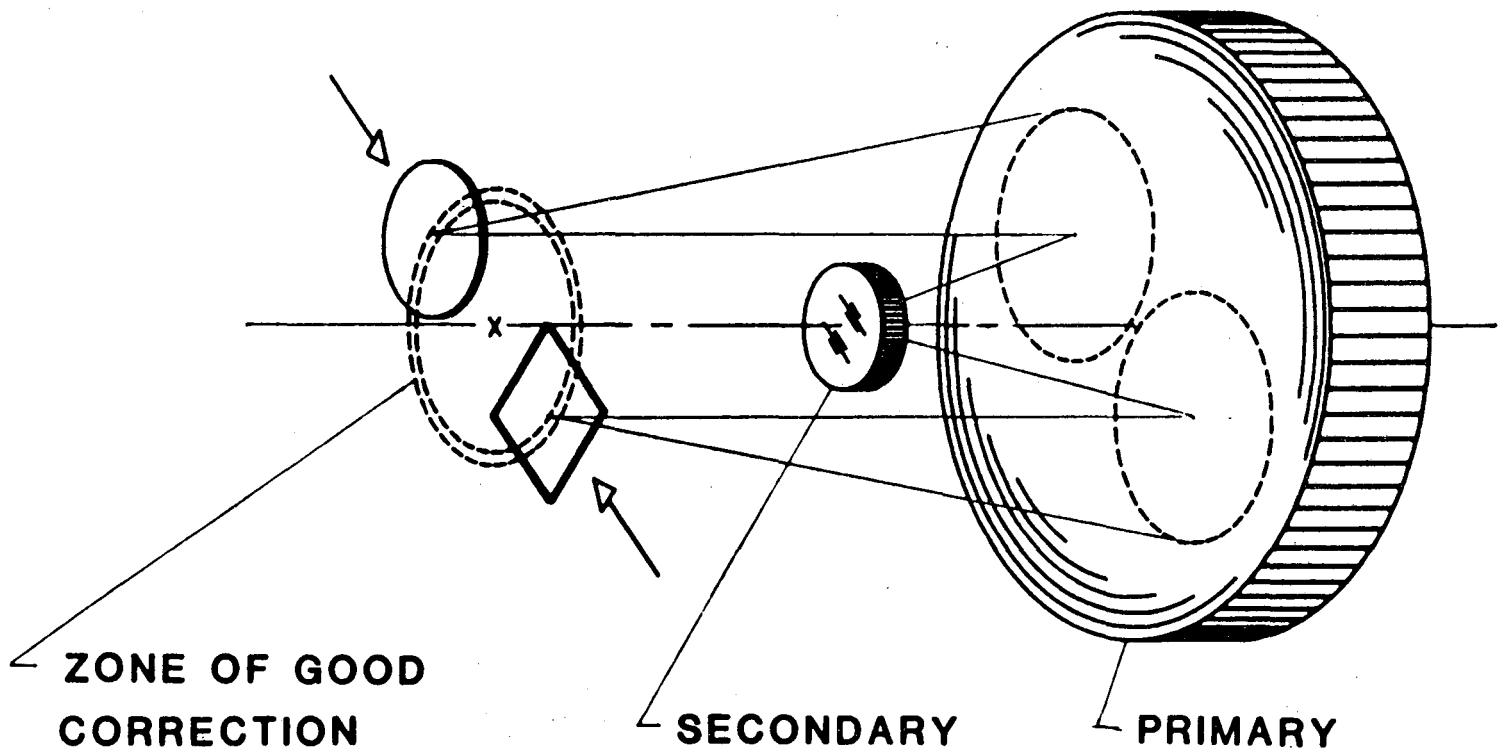

SOFT-X-RAY IMAGE INTENSITY
WAVELENGTH 14 NM
1.000
0.500
0.000
1.000E-4
2.000E-4
3.000E-4
4.000E-4
5.000E-4
POSITION (MM)



res. ≈ 0.04 μm DOF ≈ ± 0.27 μm

RING-FIELD OPTICAL SYSTEM

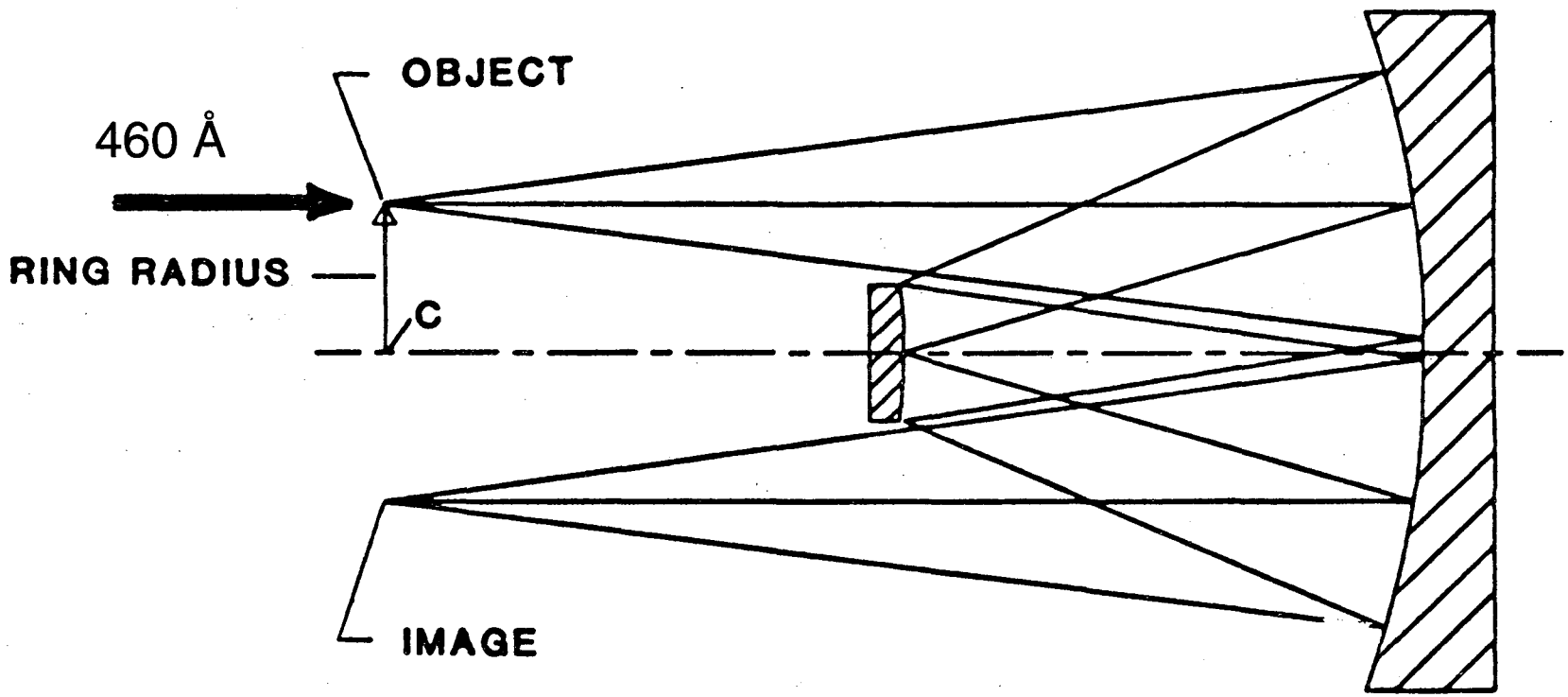
1:1 imaging



Ref. A. Offner, Optical Engineering 14, 130 (1975).

1:1

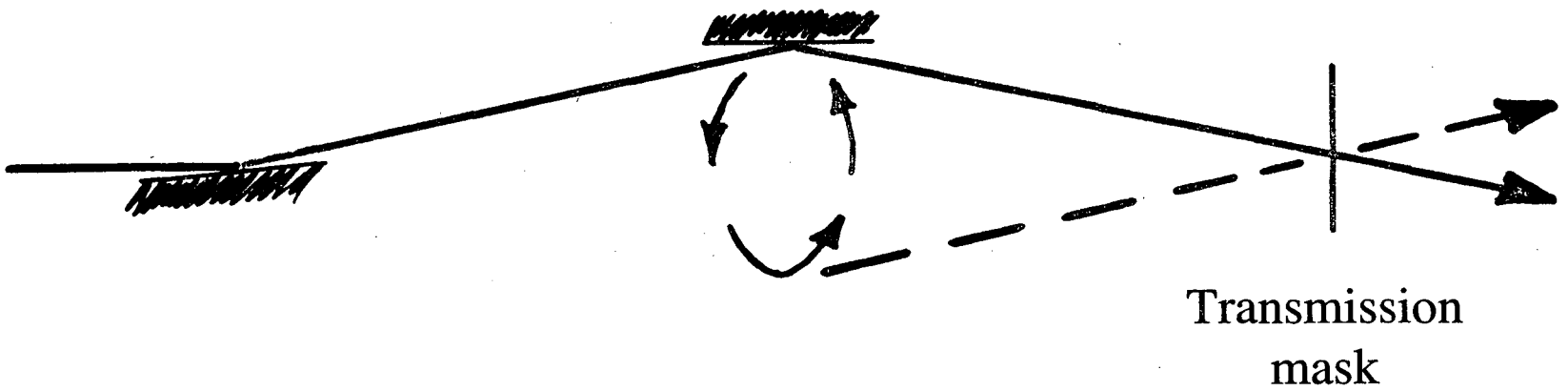
RING-FIELD OPTICAL SYSTEM



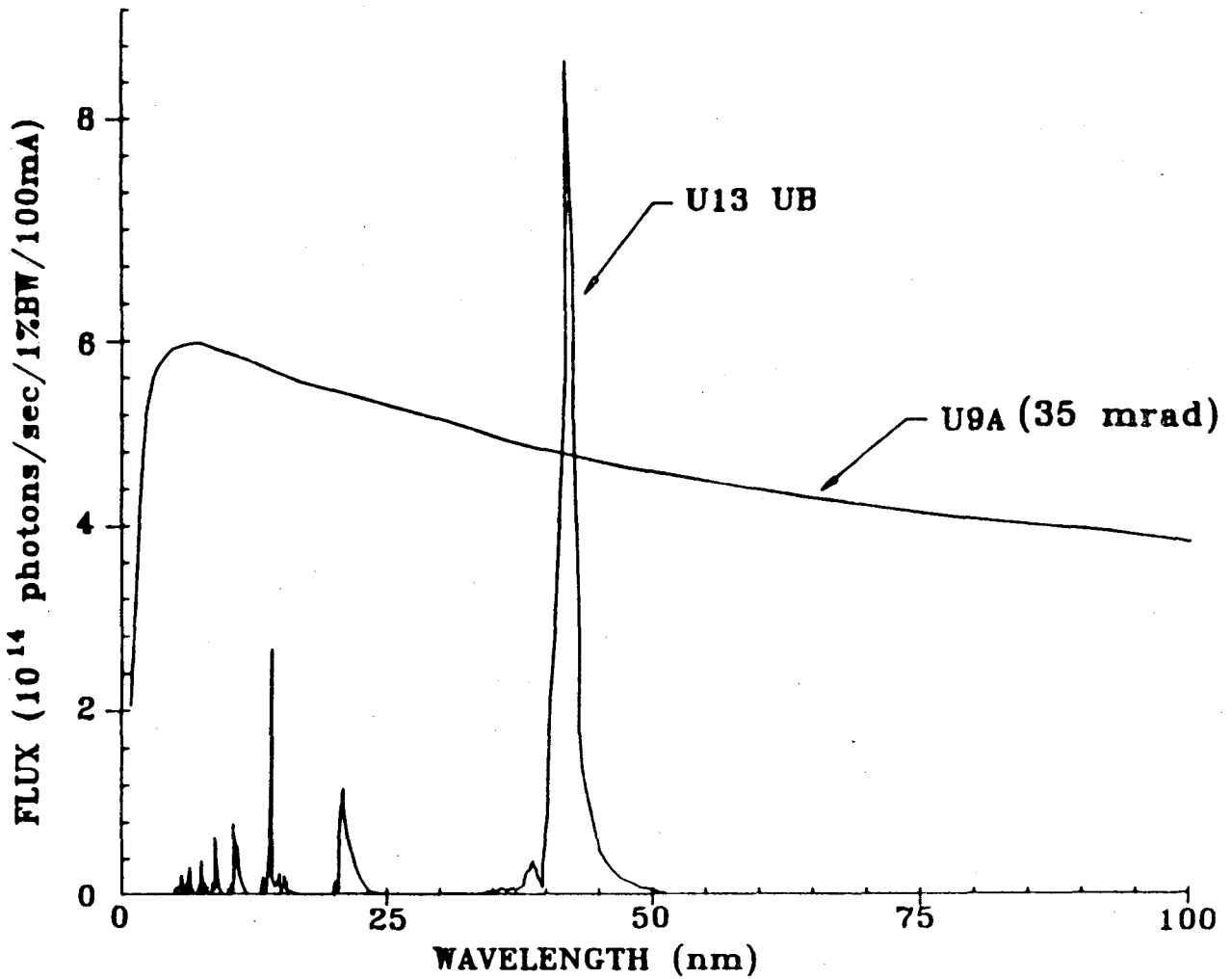
PE micralign – Model 300

Rotater or "Coherence Buster"

To improve image quality



SOURCE REQUIREMENTS



Precision Surface Figures on Aspheres

Diffraction limit $\Rightarrow$ error $< \frac{\lambda}{4}$ at wafer!

For n mirror system,

$$\sqrt{n}\, 2\delta < \frac{\lambda}{4}$$

or

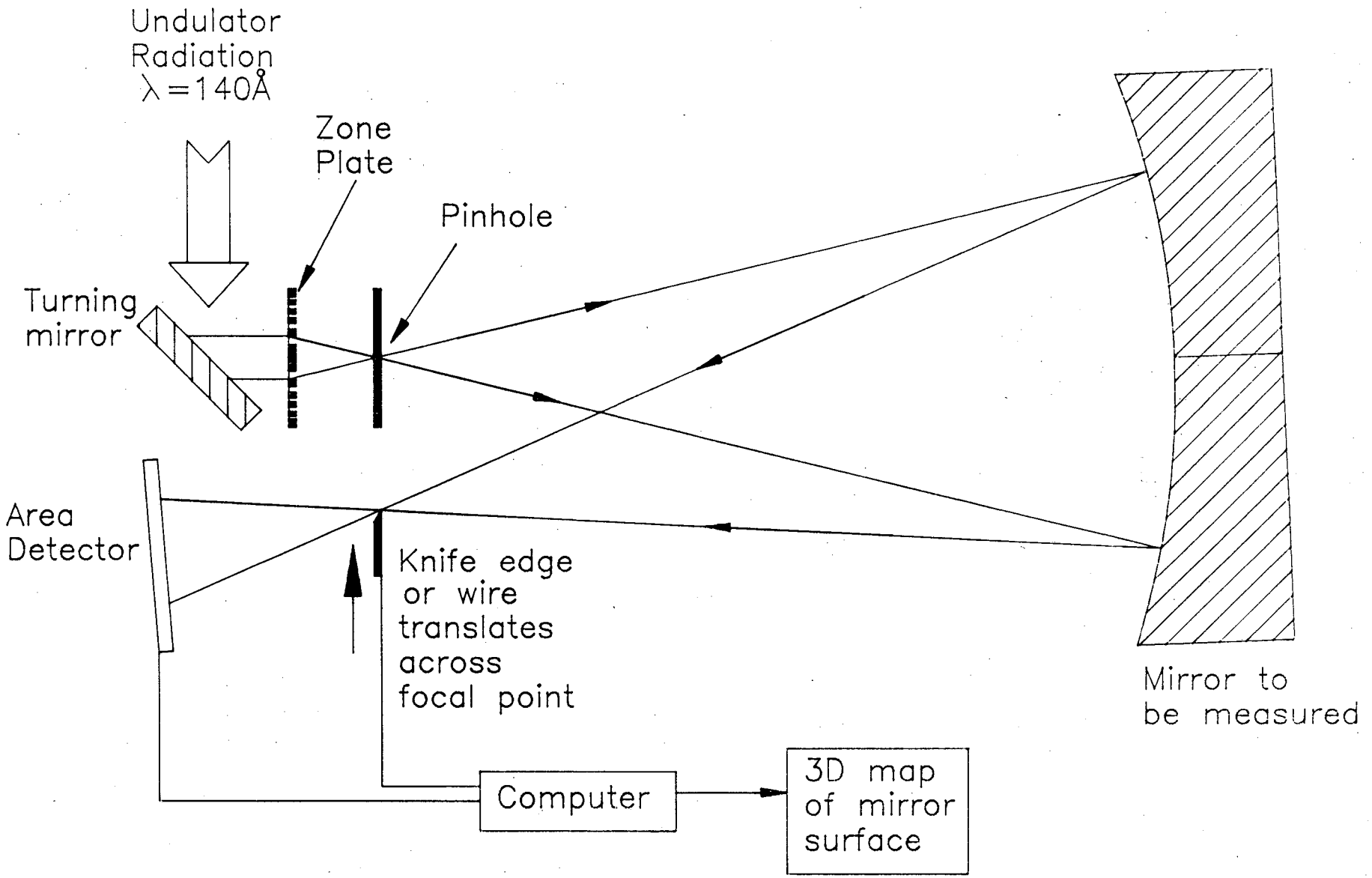
$$\delta < \frac{\lambda}{8} \sqrt{n} \text{ per mirror}$$

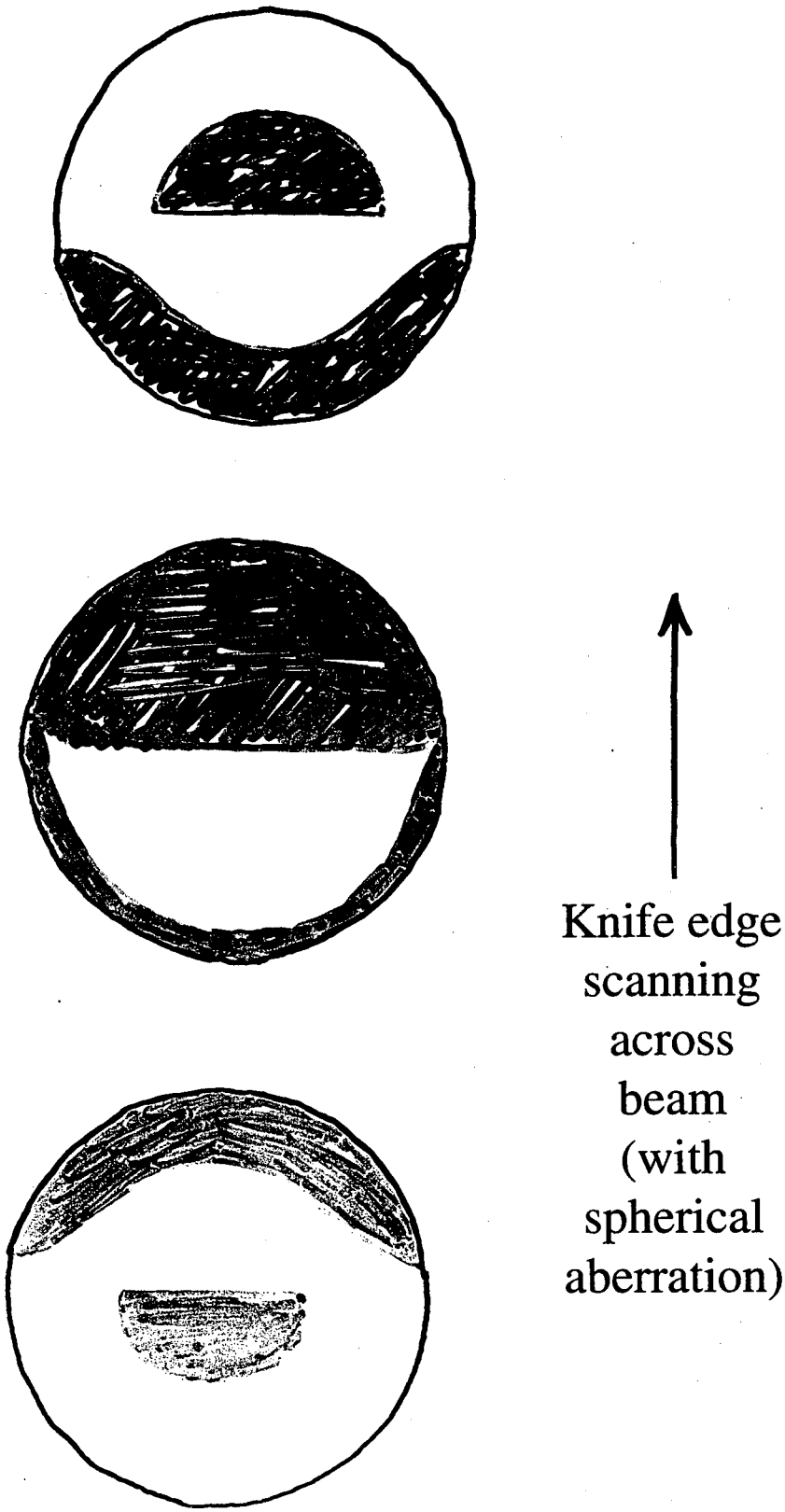
$$\Rightarrow \underline{\delta < 8 \text{ Å for } n = 4} \text{ !}$$

Beyond current state of art -
cannot measure to this accuracy!

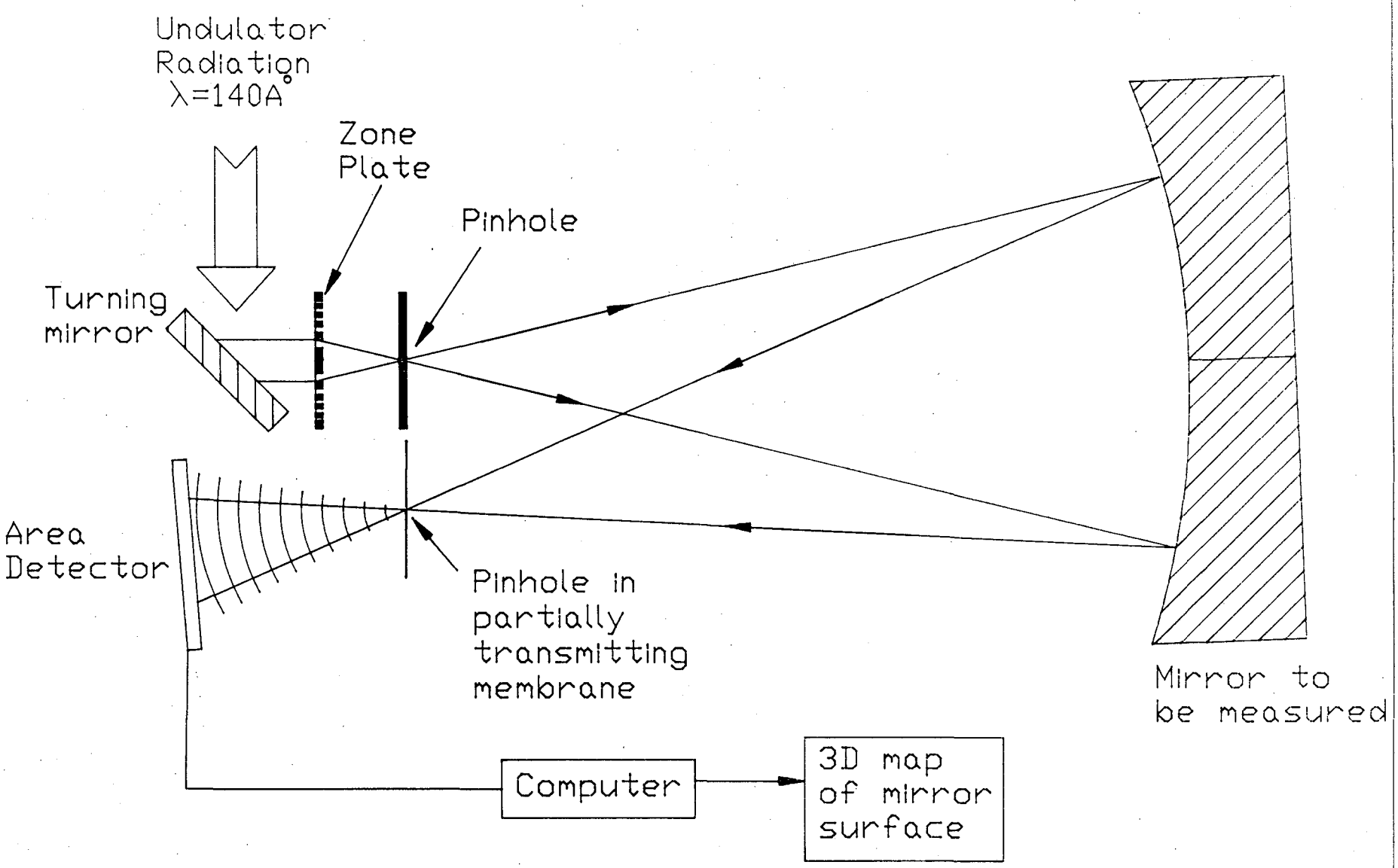
Need improved optical tests

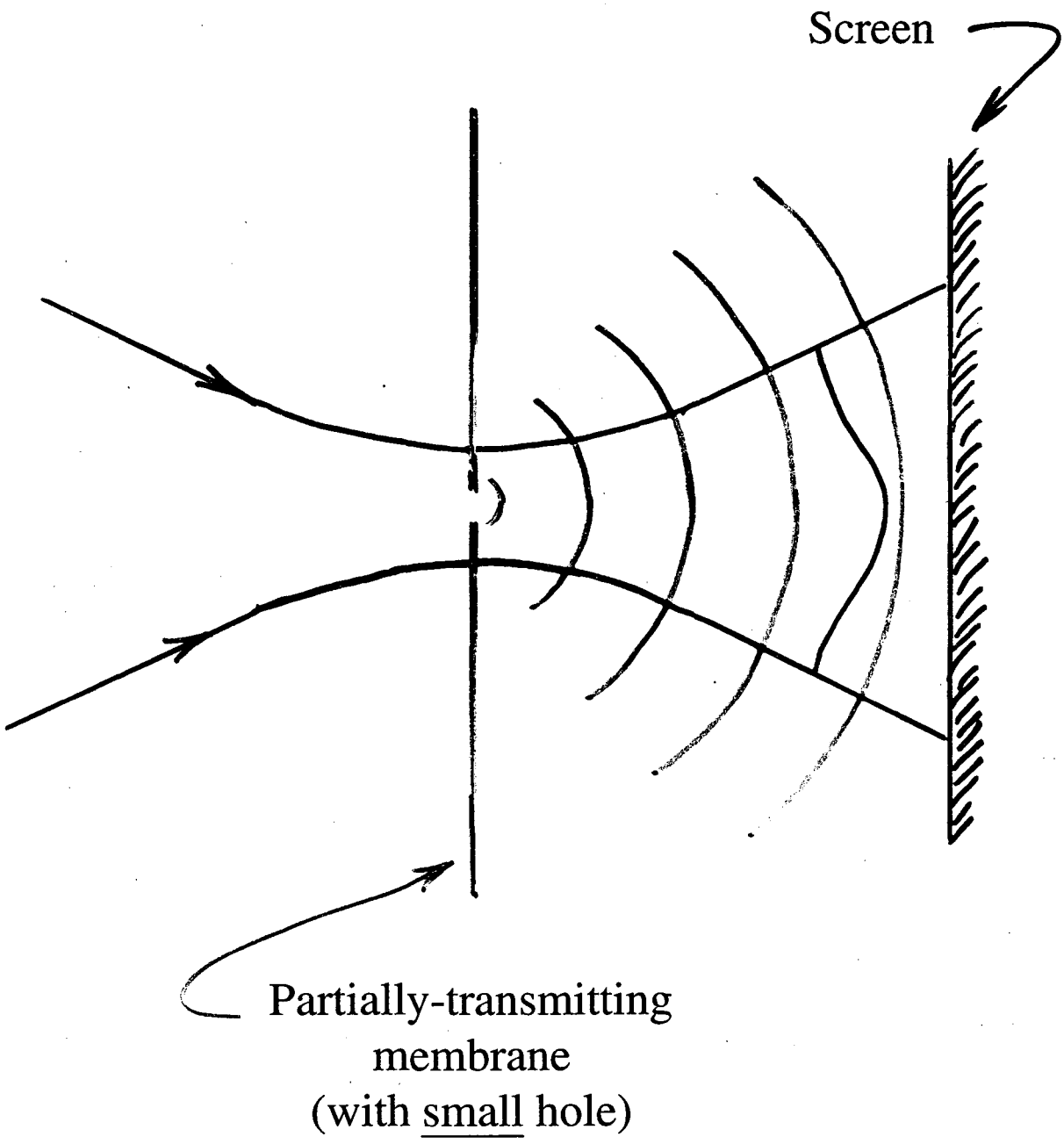
SCHLIEREN TESTS




Knife edge
scanning
across
beam
(with
spherical
aberration)

SMARTT INTERFEROMETER





Nearly common-path interferometer

Optical Testing with Undulators

Why an undulator?

- Zone plate

  — Small beam area.
  — Spatial coherence.
  — Narrow BW.

- High brightness means

  — Good throughput.
  — Good S/N.

Summary

- Small image field systems:

  Undulator is excellent match.

  Schwarzschild and Offner systems are both commercially available.

- Future large field systems:

  Bending magnet radiation.

  Precision aspheres.

- Optical testing required:

  Undulators.

Resist Characterization and Profile Simulation

A.R. Neureuther, UC Berkeley

- Introduction
  Carry Over from Optical Lithography
  Getting Started with SAMPLE

- Lithographic Materials
  Characterization Apparati and Techniques
  Chemically Amplified (Multi-State) Resists

- Surface Imaging Techniques
  Chemical Attachment vs Diffusion Approaches

- Optical Imaging and EM Scattering
  SPLAT - Aberrations, Phase-Shifting Masks
  TEMPEST - EM Scattering in Alignment and Masks

- 3-D Lithography Simulation
  Algorithms for Dissolution and Etching
  Beginnings of 3-D SAMPLE

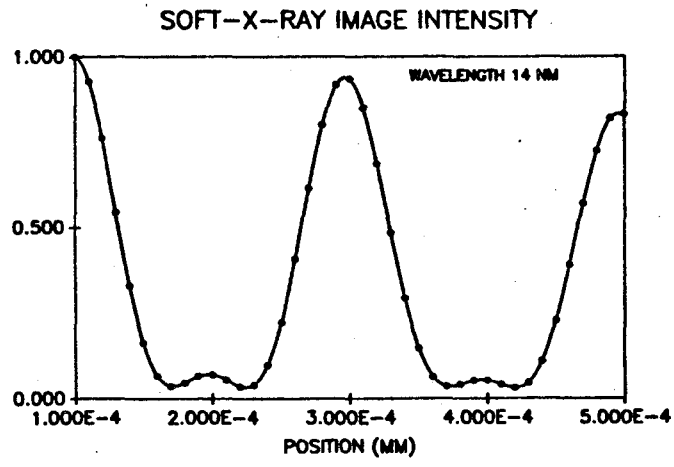
- TCAD Environments
  Integrating Processes - SIMPL-IPX
  Community Effort
  (Univ., Ind., CFI, DARPA, Commercial)

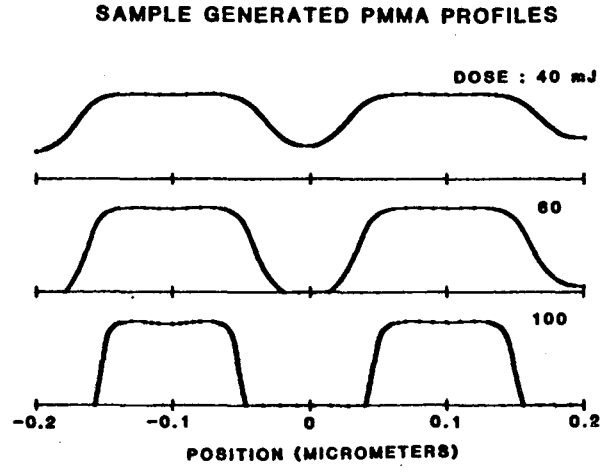
SAMPLE Simulation of Projection X-Ray
O. Wood, et al. AT&T

```
# SAMPLE INPUT FOR PROJECTION X-RAY
#
lambda .014
proj .835
linespace 0.1 0.1
parchodef 0 .01 0
optimgexp 1 0 1 0 0
readimage
resmodel .014 0 6.2 .01 .974 -.00642 .06
layers .994 -.00368
dose 40
optdevelop 1 1 0
devrate 1 .1 .048 2
devtime 60
developrun
```

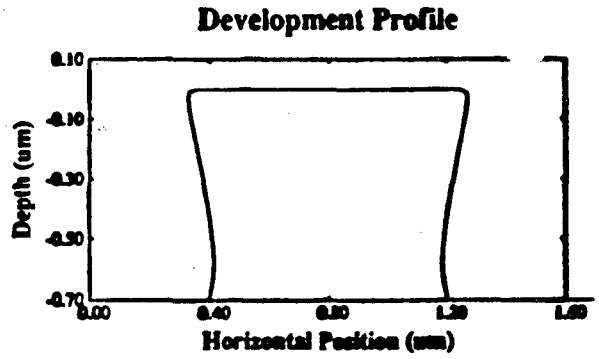
CODE V

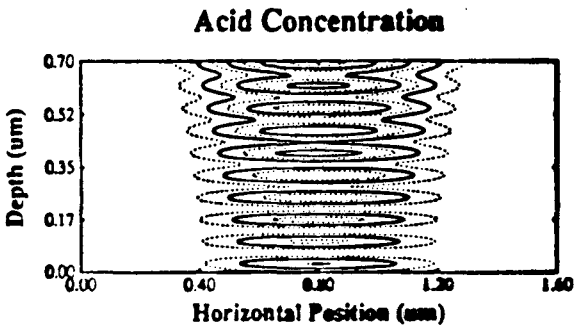
$$R = \frac{R_0}{\left(1 + \frac{E}{E_0}\right)^{\alpha}}$$

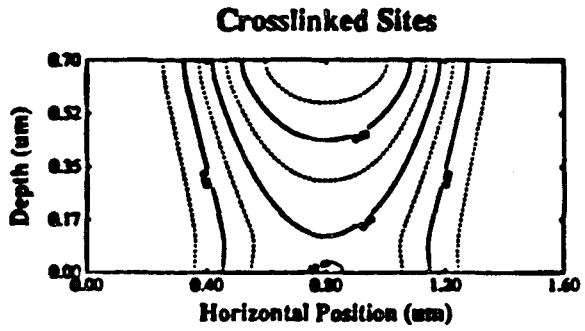




Example of Multi-State SAMPLE Display







Comparison of Simulation with Experiment

Imaging:

Linewidth = 0.3 μm

NA = 0.42

Exposure:

Dose(exp.) = 18 mJ/cm^2

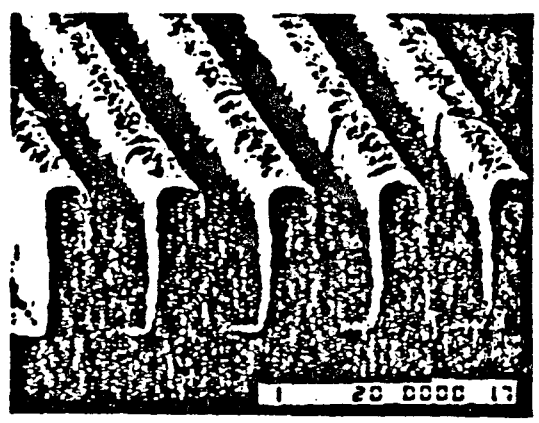
Dose(sim.) = 1.4 x 18 mJ/cm^2

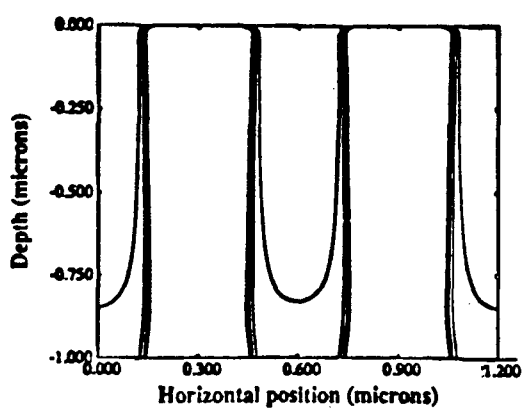
= 25.2 mJ/cm^2

Bake:

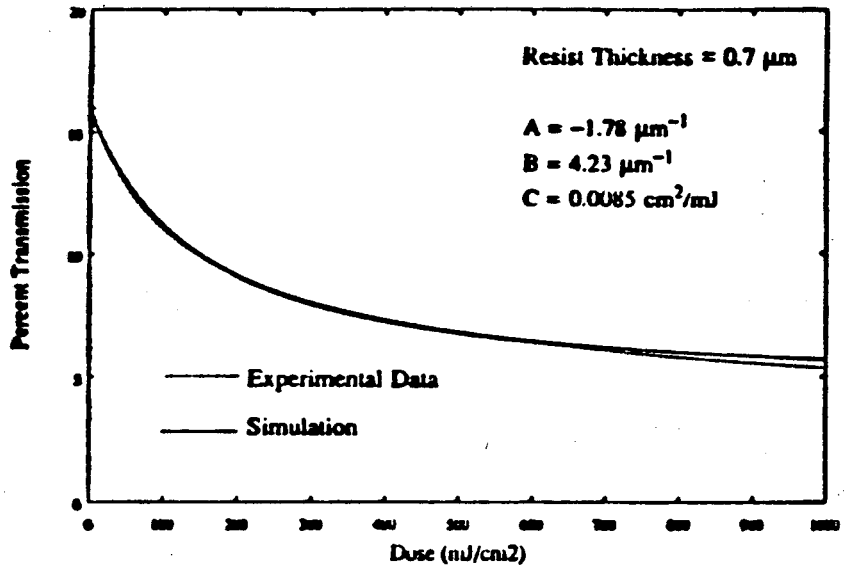
Temperature = 140°C

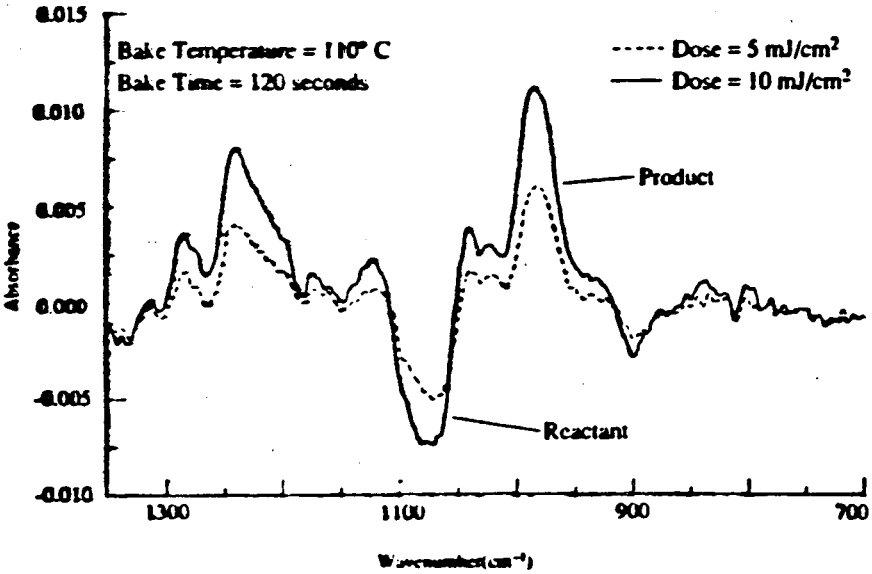
Time = 60 seconds





Model for Shipley XP-8798 Resist

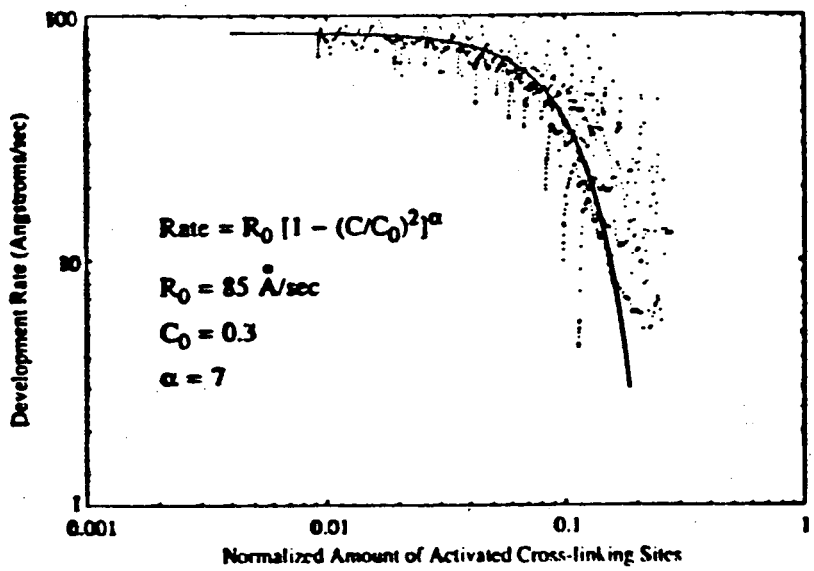


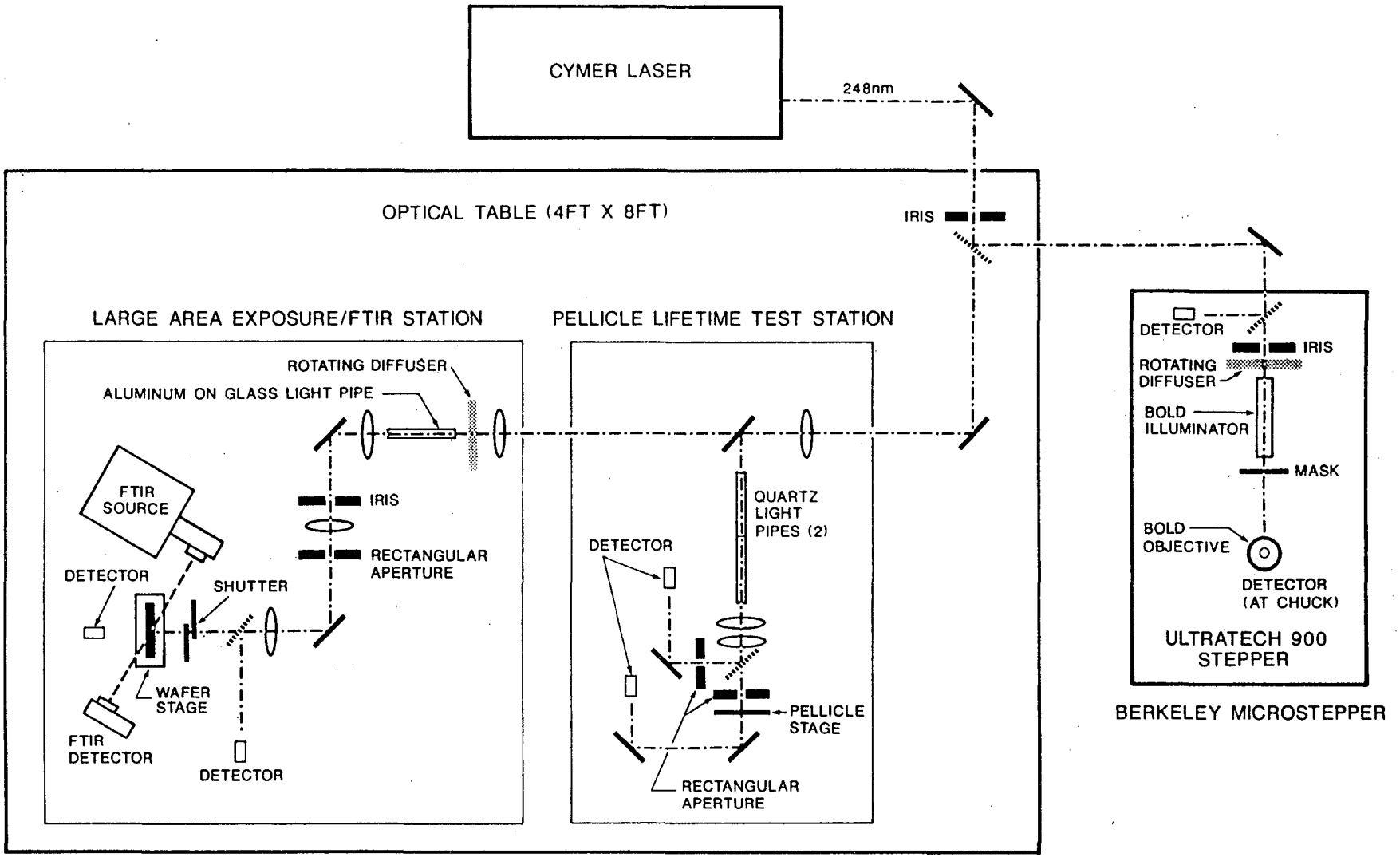


$$\frac{\partial C_{US}}{\partial t} = -K_1 C_A C_{US}$$

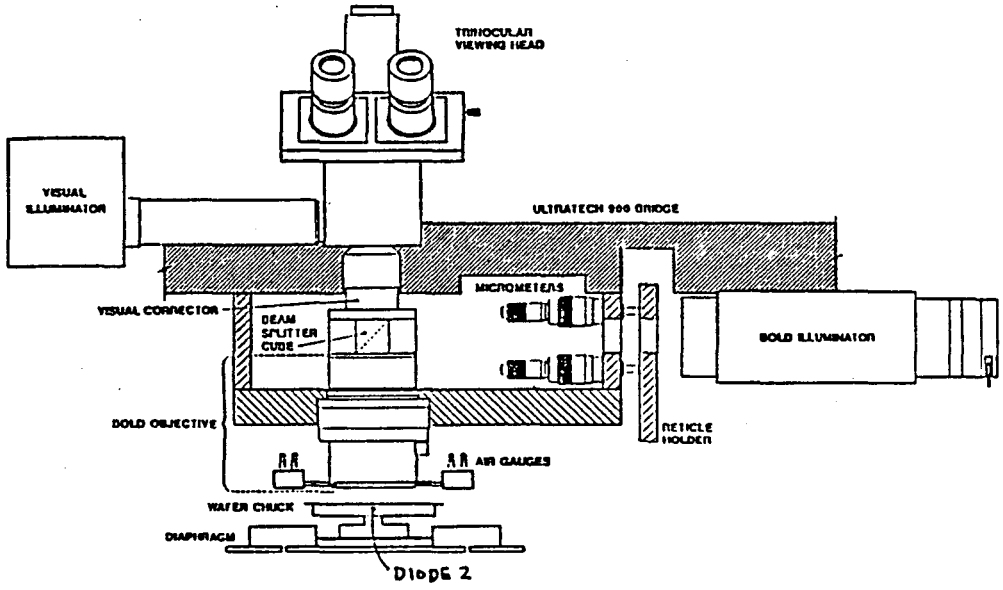
$$\frac{\partial C_{AS}}{\partial t} = K_1 C_A C_{US}$$

$$\frac{\partial C_A}{\partial t} = K_2 C_A$$

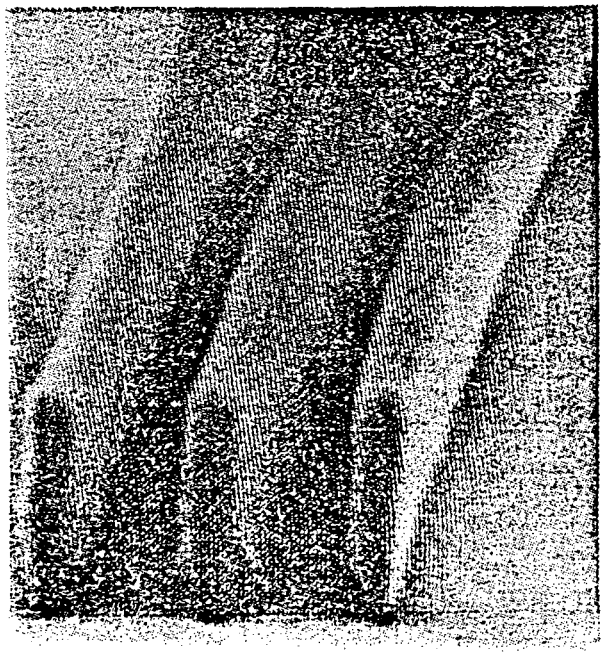




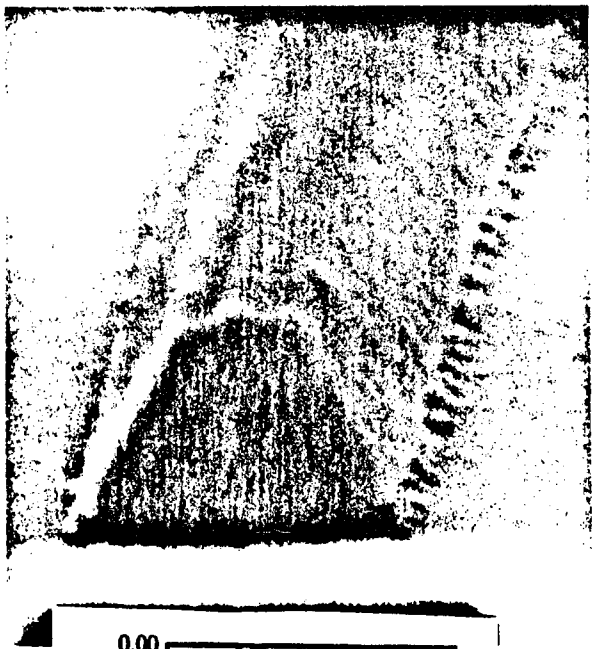
248nm OPTICAL CHARACTERIZATION FACILITY AT UC BERKELEY (10/89)

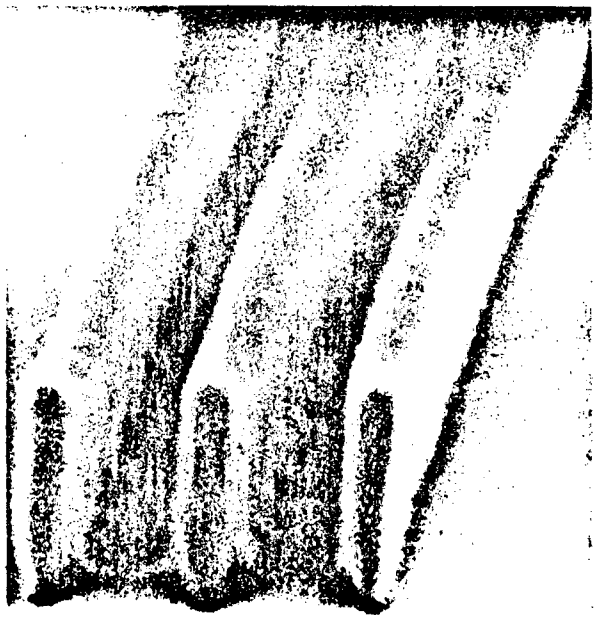


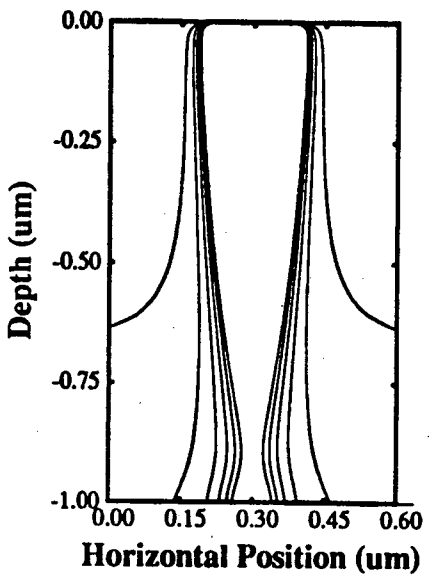
THE BERKELEY MICROSTEPPER



- 0.3μm features resolved in experimental resists (Shipley xp8843).






0.00
-0.25
-0.50
-0.75
-1.00
Depth (um)
0.00
0.15
0.30
0.45
0.60
Horizontal Position (um)

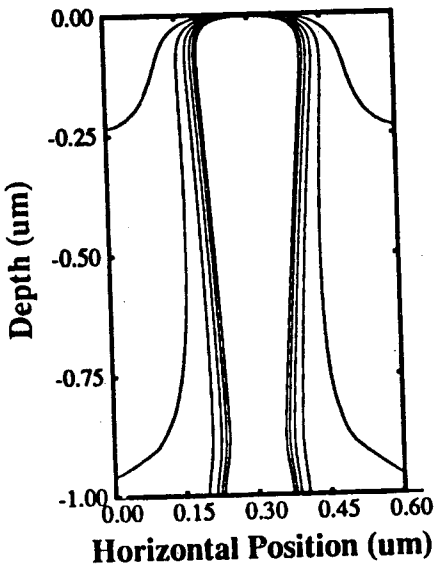
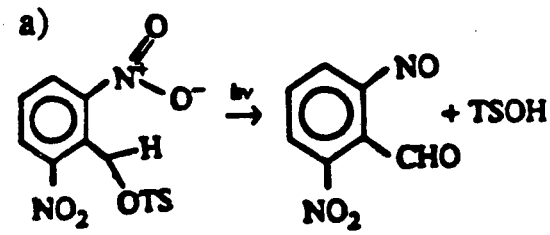

0.00
-0.25
-0.50
-0.75
-1.00
Depth (um)
0.00
0.15
0.30
0.45
0.60
Horizontal Position (um)

Figure 2: Acid generation reaction for a) the tosylate and b) the onium salt.



b)

$$Ar_3S^+AsF_6^- \xrightarrow[RH]{h\nu} Ar_2S + Ar^\bullet + R^\bullet + HAsF_6$$

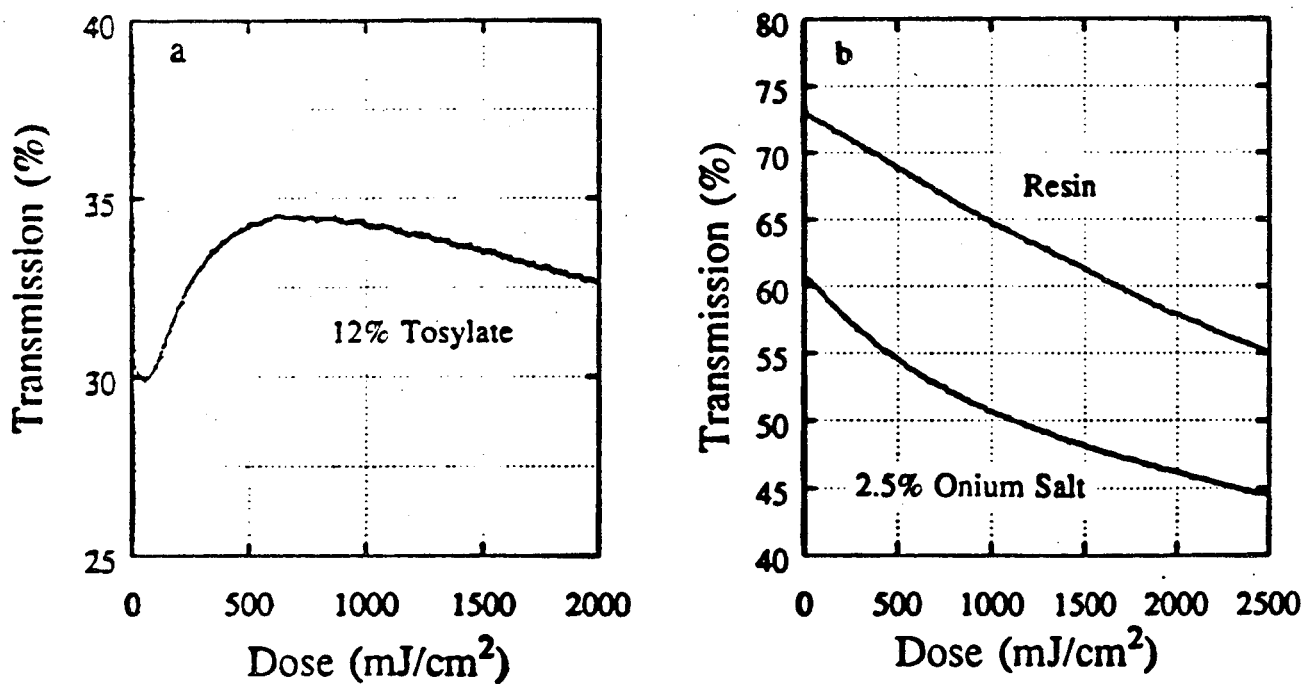


Figure 3: Transmission versus exposure dose for a) the 12% tosylate mixture, b) the 2.5% onium salt mixture and the resin alone.

The Bake Model

The following kinetic equations were used to model the post-exposure bake.

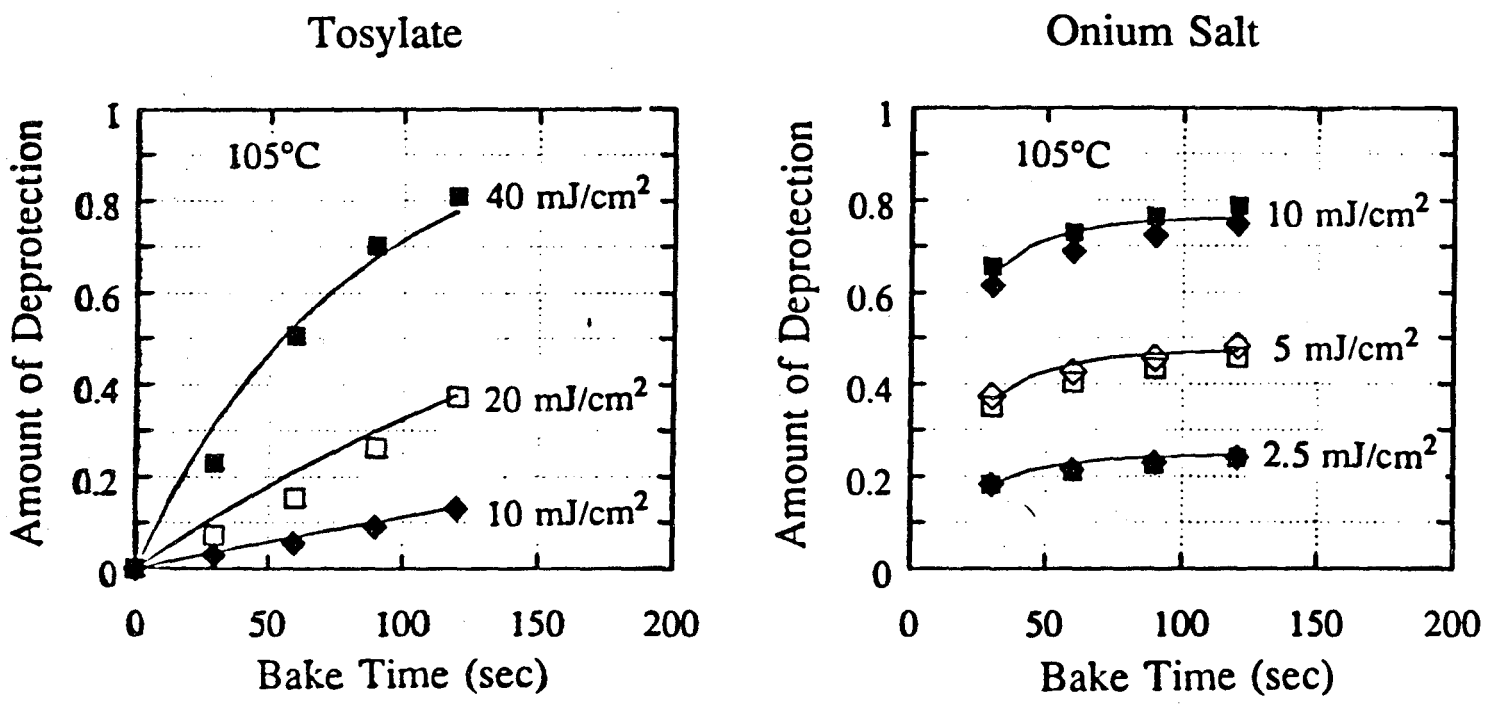
Deprotection reaction:

$$\text{Rate of deprotection} = k_1[\text{t-BOC}][\text{acid}]^m$$

Acid loss reaction:

$$\text{Rate of acid loss} = k_2[\text{acid}]$$

The rate constants, k_1 and k_2, and the acid exponent, m, were determined by fitting the model to the FTIR measurements of deprotection.



A comparison between the kinetic models (solid lines) and the FTIR measurements of deprotection (points) for the resists with both the tosylate and the onium salt PAG's.

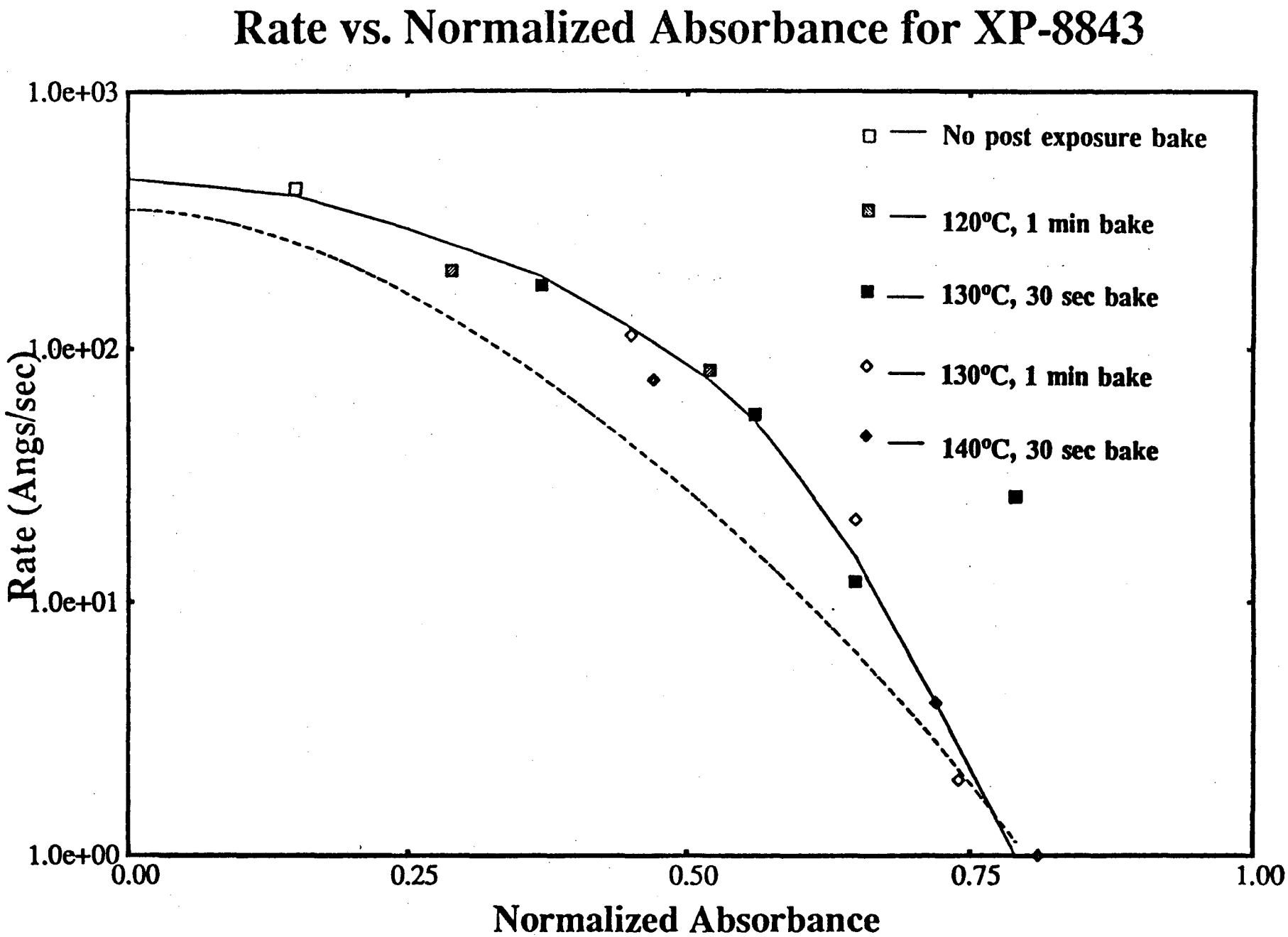


Figure 5. Dissolution rate versus normalized Δ-absorbance for electron-beam (points and solid curve) and optically (dotted curve) exposed XP-8843.

PARMEX-PIX

QUIT | FILE | SYSTEM | INFO | DATA/SPEC | CONDITIONING | TRANSF | PLOT

DATA
MODEL
SAMPLE
PARMEX

WELCOME TO PIX!

No name

INPUT PLOT FILENAME:

26.1

SET SCALES | PLOT

No name

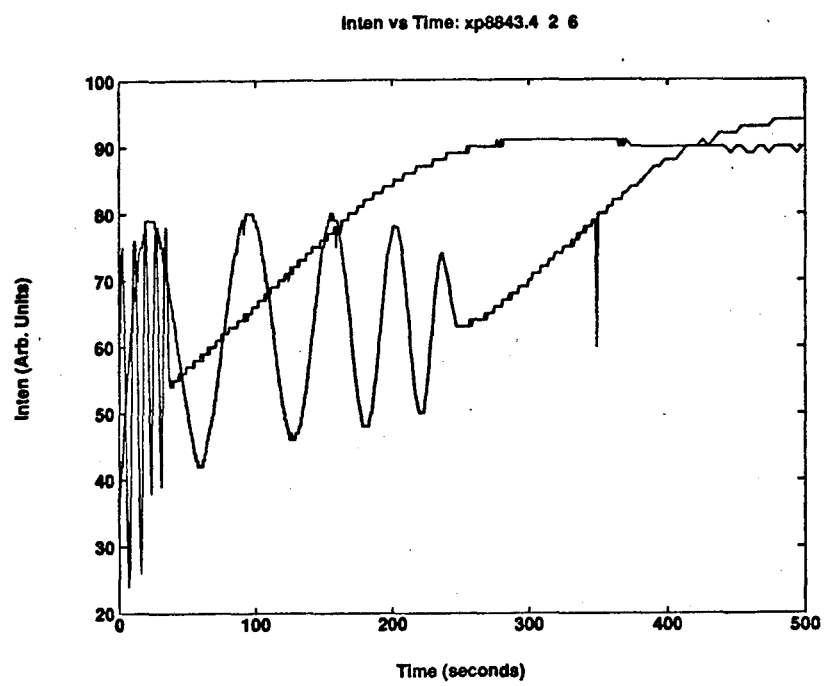
SELECT PLOT TYPE:

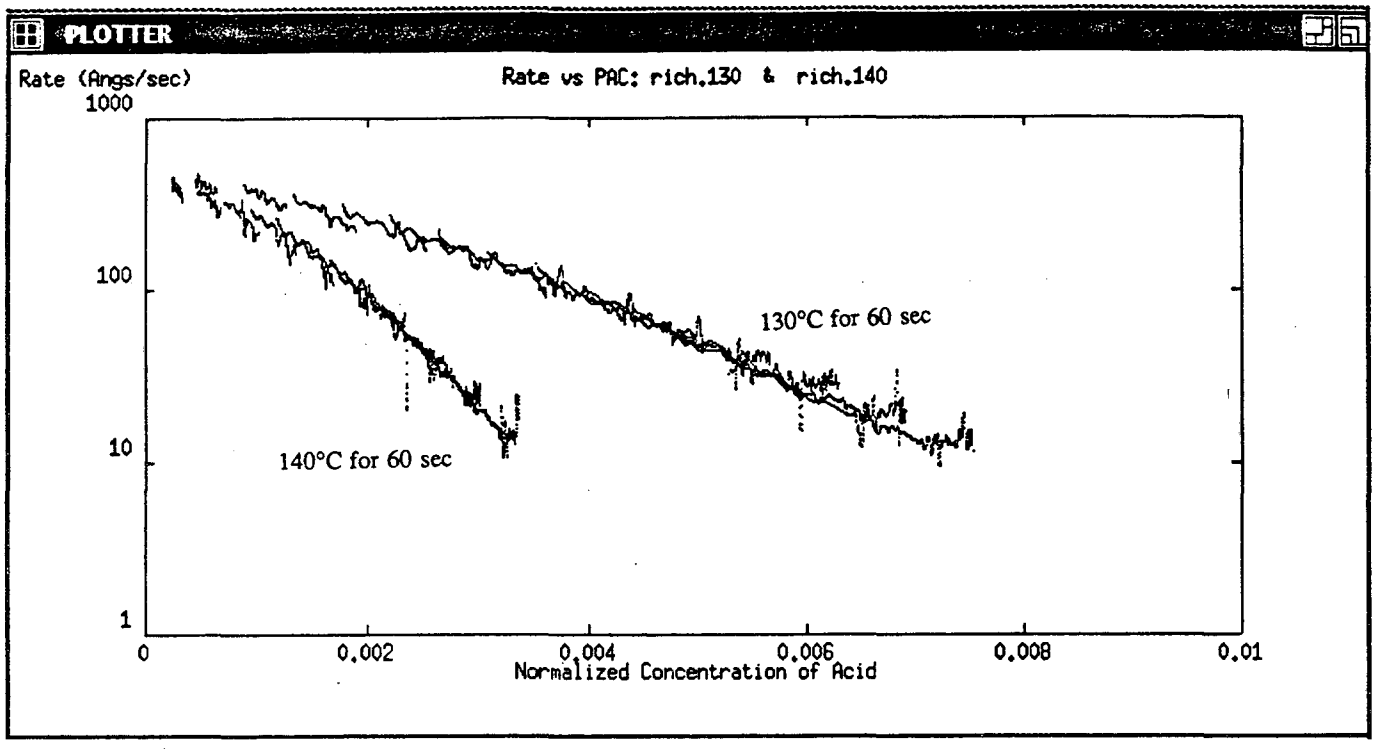
INTENSITY vs TIME | THICKNESS vs TIME | RATE vs TIME

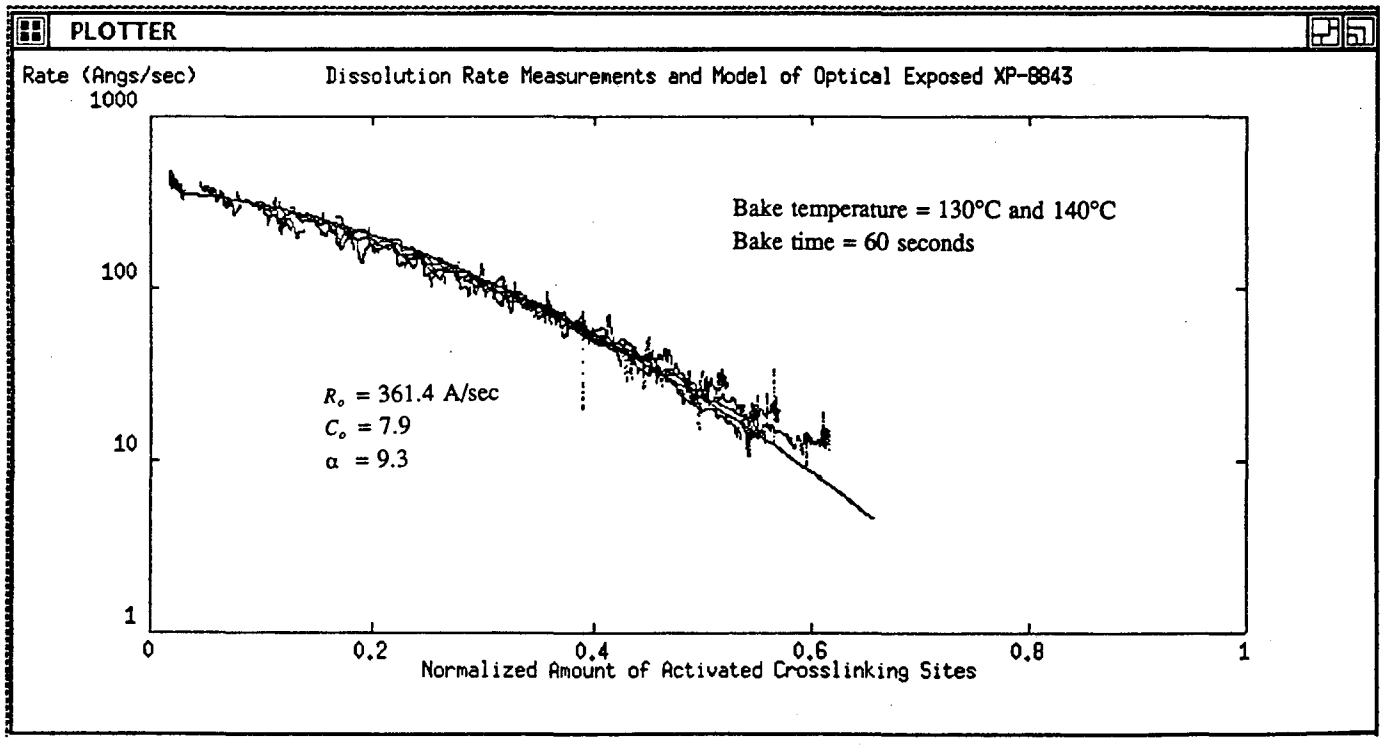
RATE vs DEPTH | PAC vs DEPTH | RATE vs PAC

CONSOLE TEXT VIEWPORT

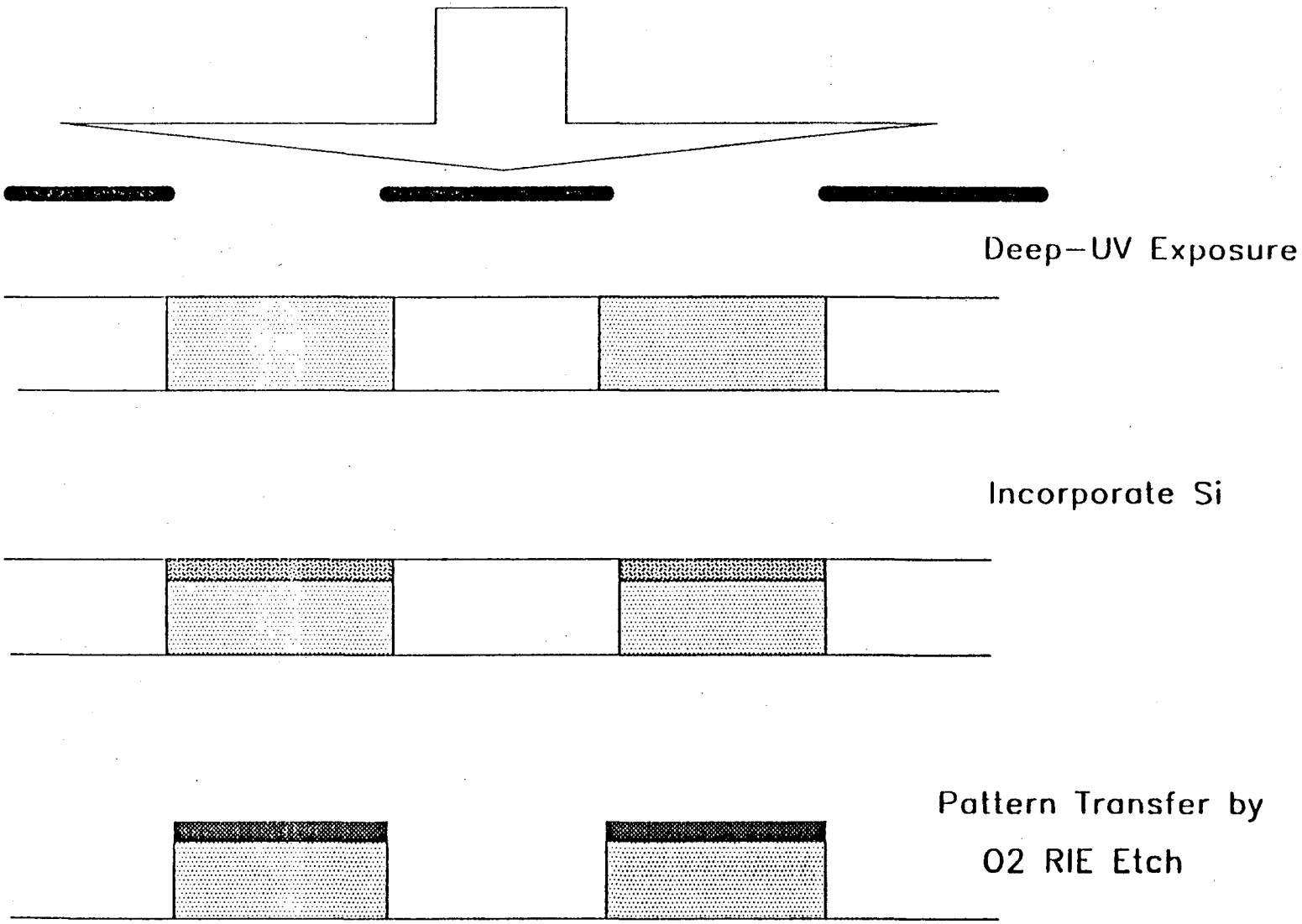
```
Console> quit

** PARMEX: Parameter Extractor
** Resist Dissolution Data Analysis Pr
** Wed Oct 28 14:47:54 PST 1987  WRB II
** Version 1.0-Beta
** Revision Dec 4, 1989

parmex>  load /users/achiu/PIX/src/data/shipley refl

Wafer  : xp8843.4
Resist : xp8843                Thicknes:
Surface: hardbake              Thicknes:
Lambda : 6328.0 (measure)      Index. re
Lambda : 2480.0 (expose)       Index. re
Develop: mf312                 Temperatu
Dose   :  1.00 ..   0.00            Ti
Extrema:  9.. 11
parmex>  push 2

parmex>  add 6

parmex>  plot data
```



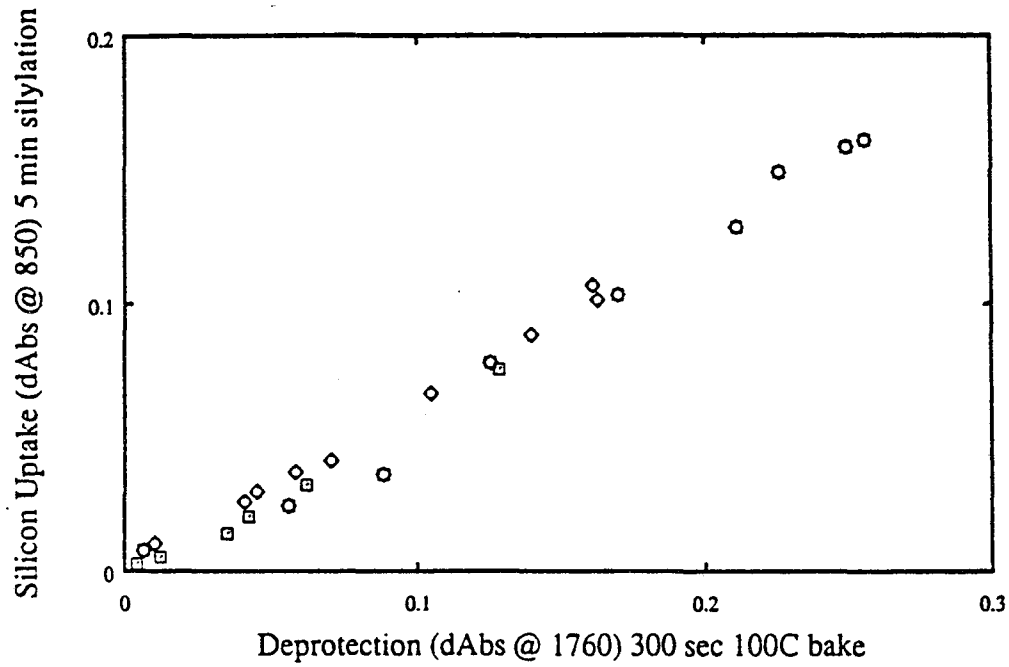

PLOTTER
Rate (Angs/sec)
Rate vs PAC: rich.130 & rich.140
1000
100
10
1
0
0.002
0.004
0.006
0.008
0.01
Normalized Concentration of Acid
130°C for 60 sec
140°C for 60 sec


PLOTTER
Rate (Angs/sec)
Dissolution Rate Measurements and Model of Optical Exposed XP-8843
1000
100
10
1
0
0.2
0.4
0.6
0.8
1
Normalized Amount of Activated Crosslinking Sites
Bake temperature = 130°C and 140°C
Bake time = 60 seconds
R_o = 361.4 A/sec
C_o = 7.9
α = 9.3

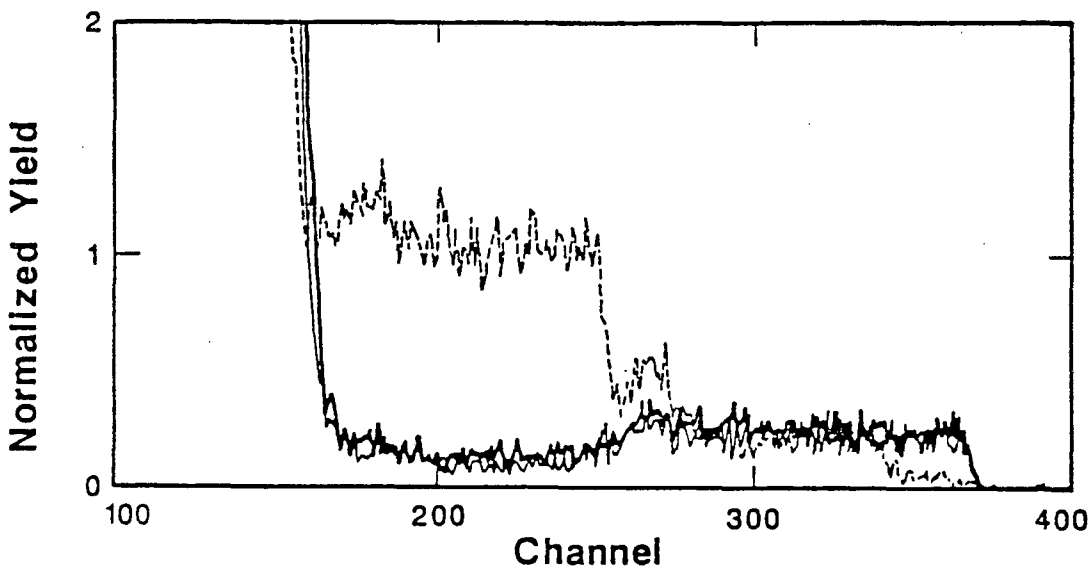
Silylation Process Flow



SILICON UPTAKE



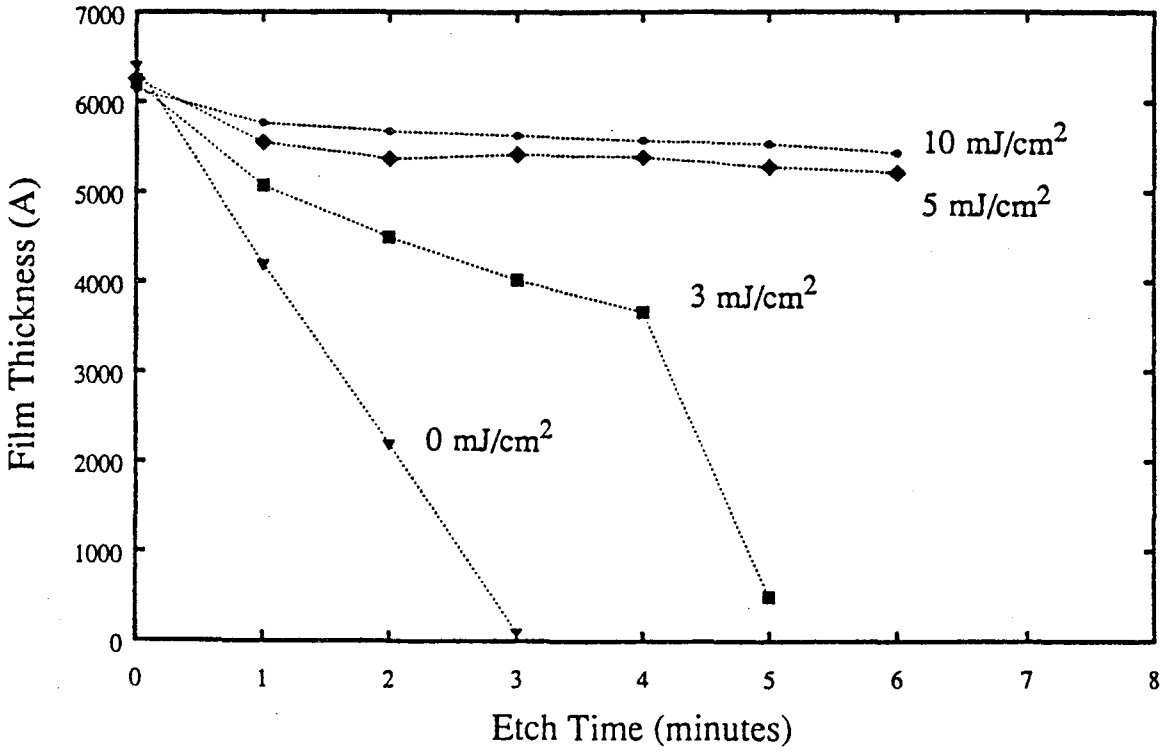
FTIR shows silicon uptake is proportional to the number of phenolic sites created during deprotection (the different symbols represent data for different co-polymers)



RBS confirms that the silicon uptake is a bulk effect (the dashed line shows the silicon distribution in a film of a 1:2 styrene:t-BOC styrene co-polymer that was completely deprotected and silylated for 5 minutes at 100°C 110Torr HMDS)

ETCH BEHAVIOR

Etch selectivity > 30:1 seen for silylated 1:2 co-polymer films



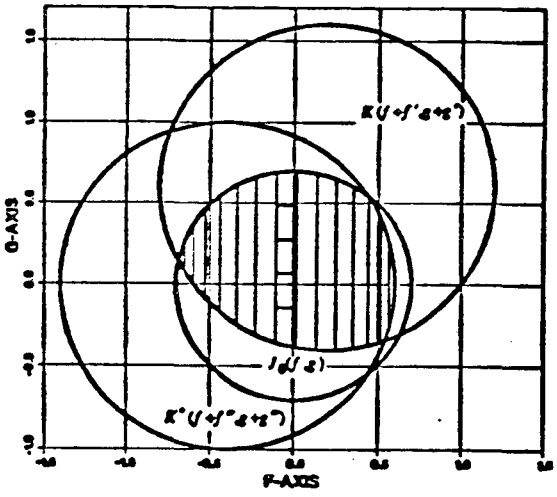
0.4μm line/space

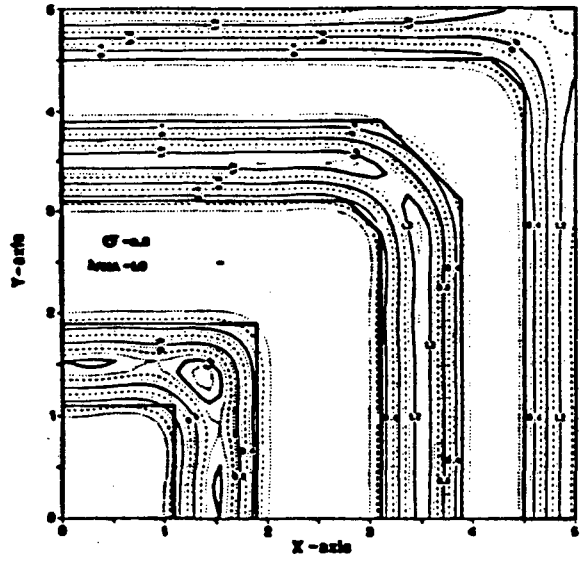
SPLAT: Simulation of Projection Lens Aberrations via TCCs

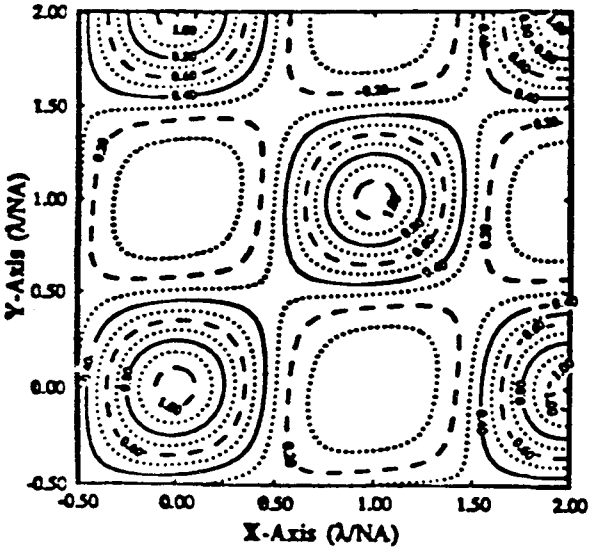
Kenny K.H. Toh

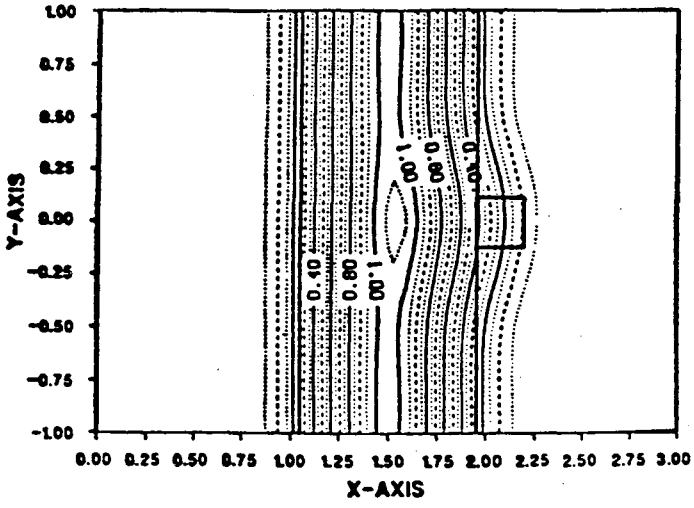
FUNCTION: Calculate two-dimensional optical aerial images for projection printing systems with lens aberrations.

KEY FEATURES: Hopkin's formulation approach, algorithm adapts to degree of aberration asymmetry, algorithm self checking, save and load of the transmission cross coefficients, can generate an input image for SAMPLE.

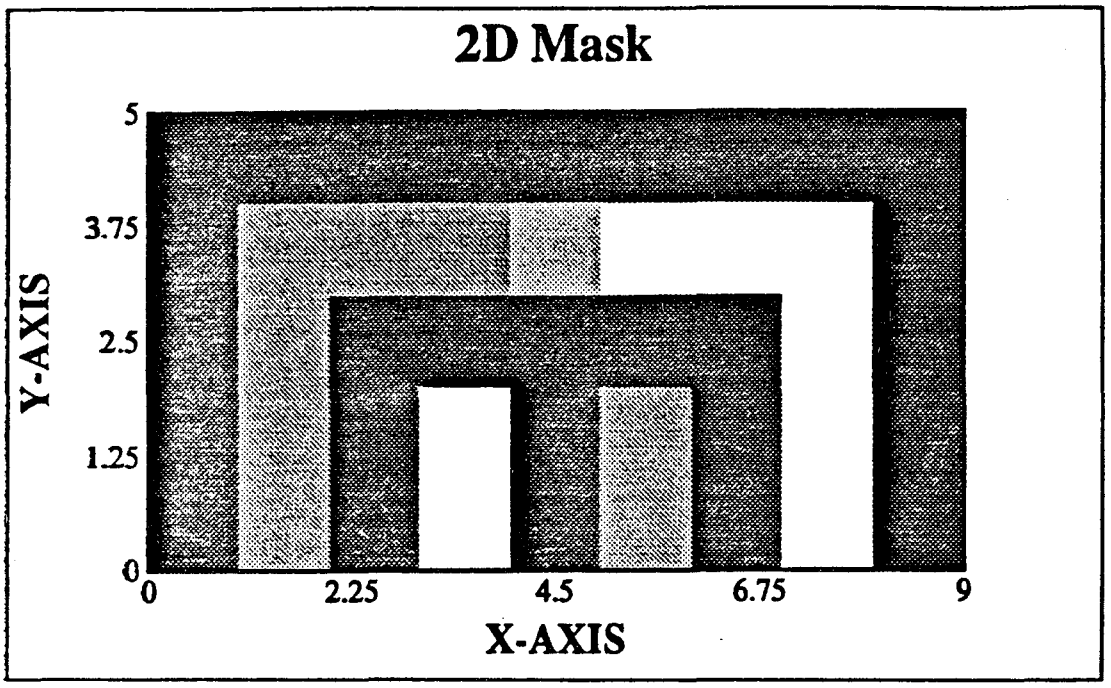








1 μm (0.64 λ/NA) Phase-Shifted Lines



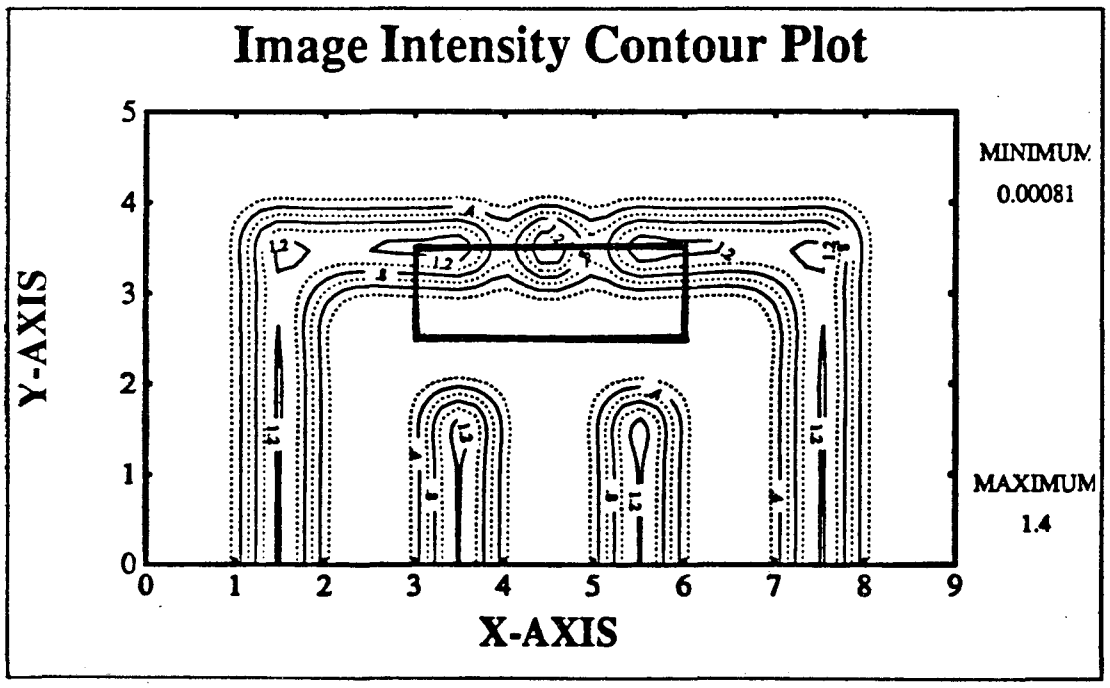
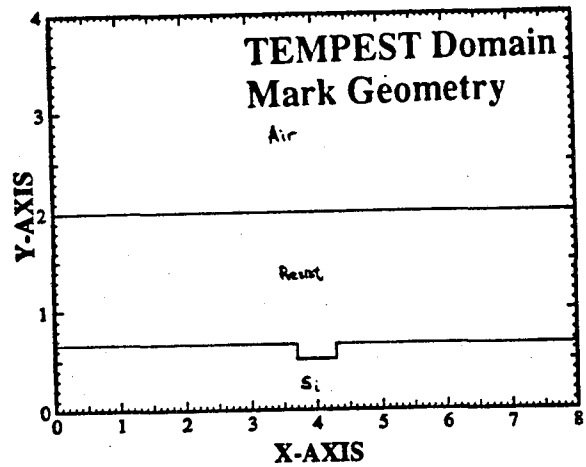


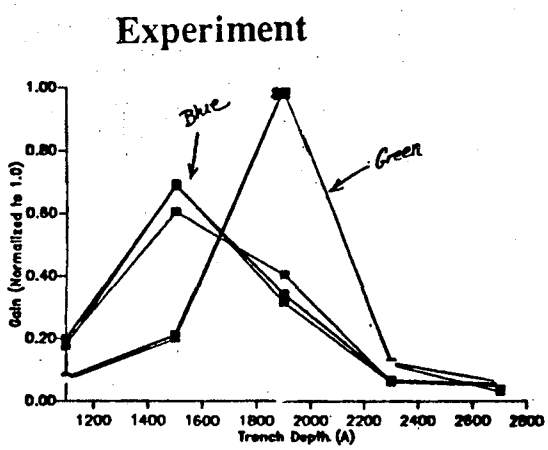
Figure 9.19: Image intensity contour plot of a phase-shifted mask pattern. The simulation was run using $\lambda = 0.436$ μm, NA=0.28 and partial coherence $\sigma = 0.5$.

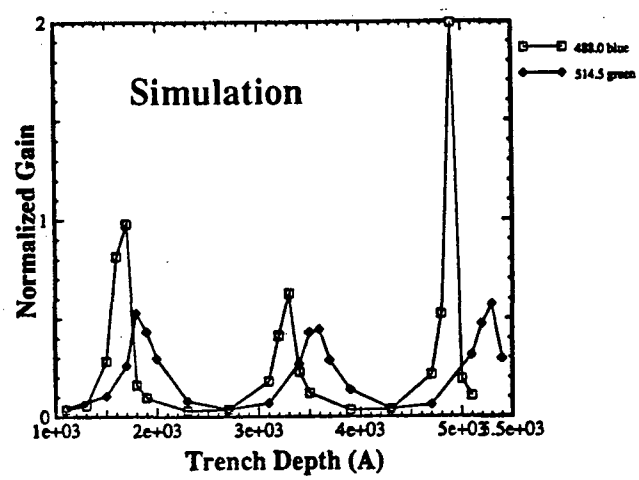
TEMPEST

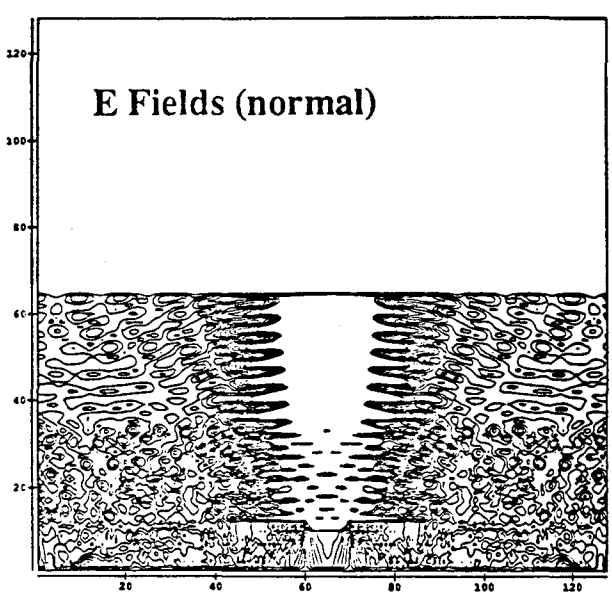
Results for Alignment

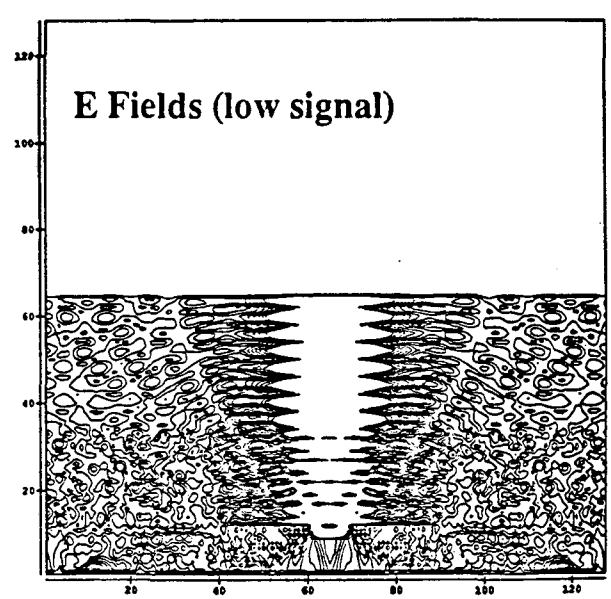
Alignment Signal Variation with Mark Geometry



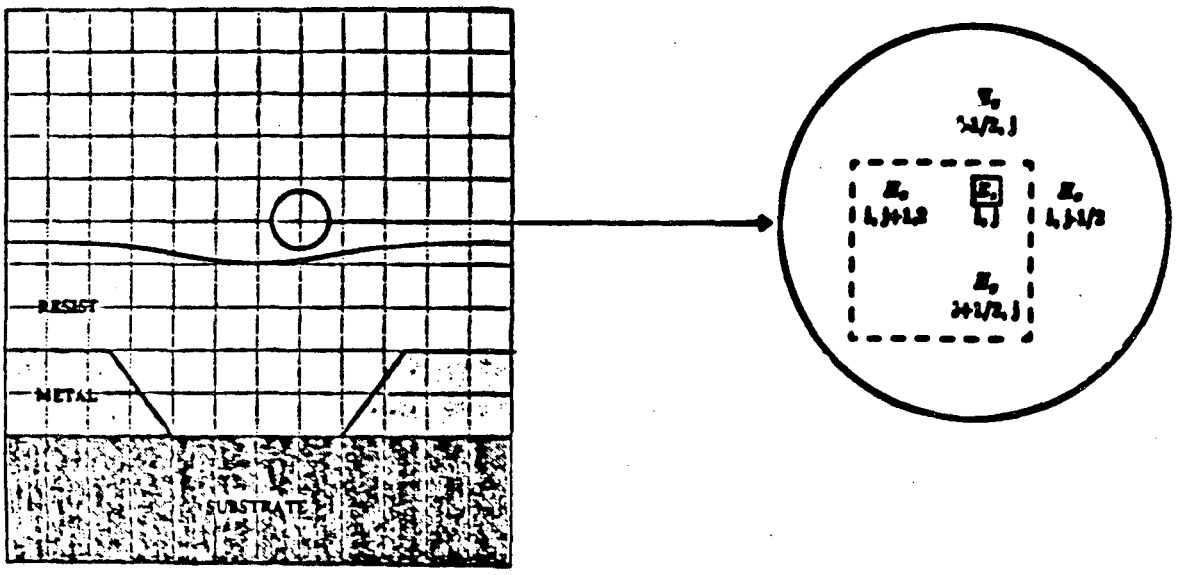








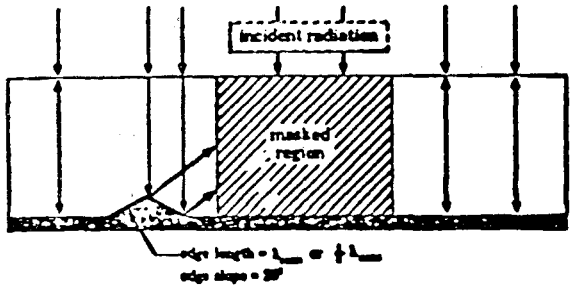
TEMPEST
Time-domain Electromagnetic [Massively Parralel] Evaluation of Scattering from Topography

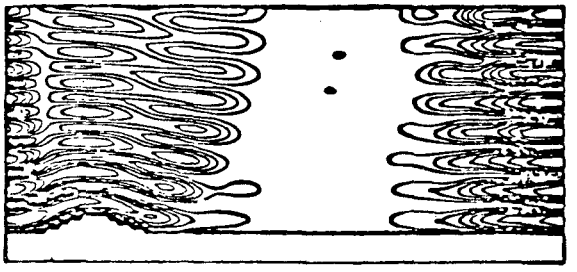


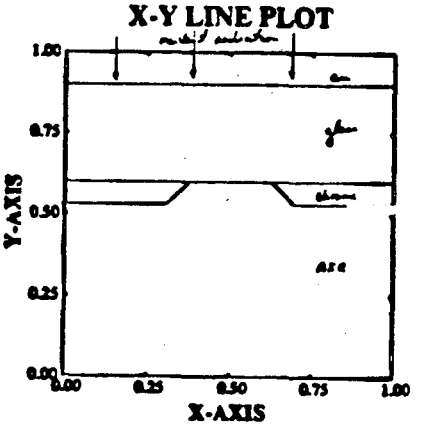
TEMPEST

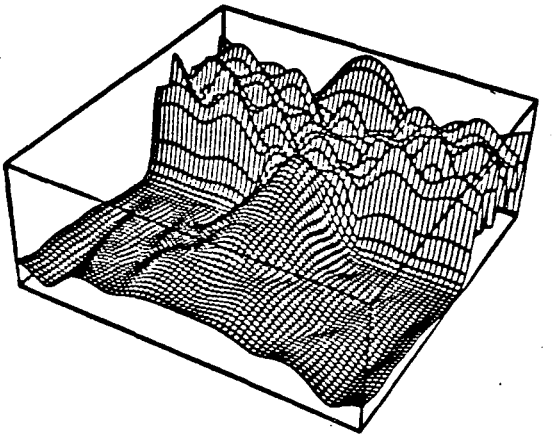
Mask Analysis

Substrate Grain Reflections

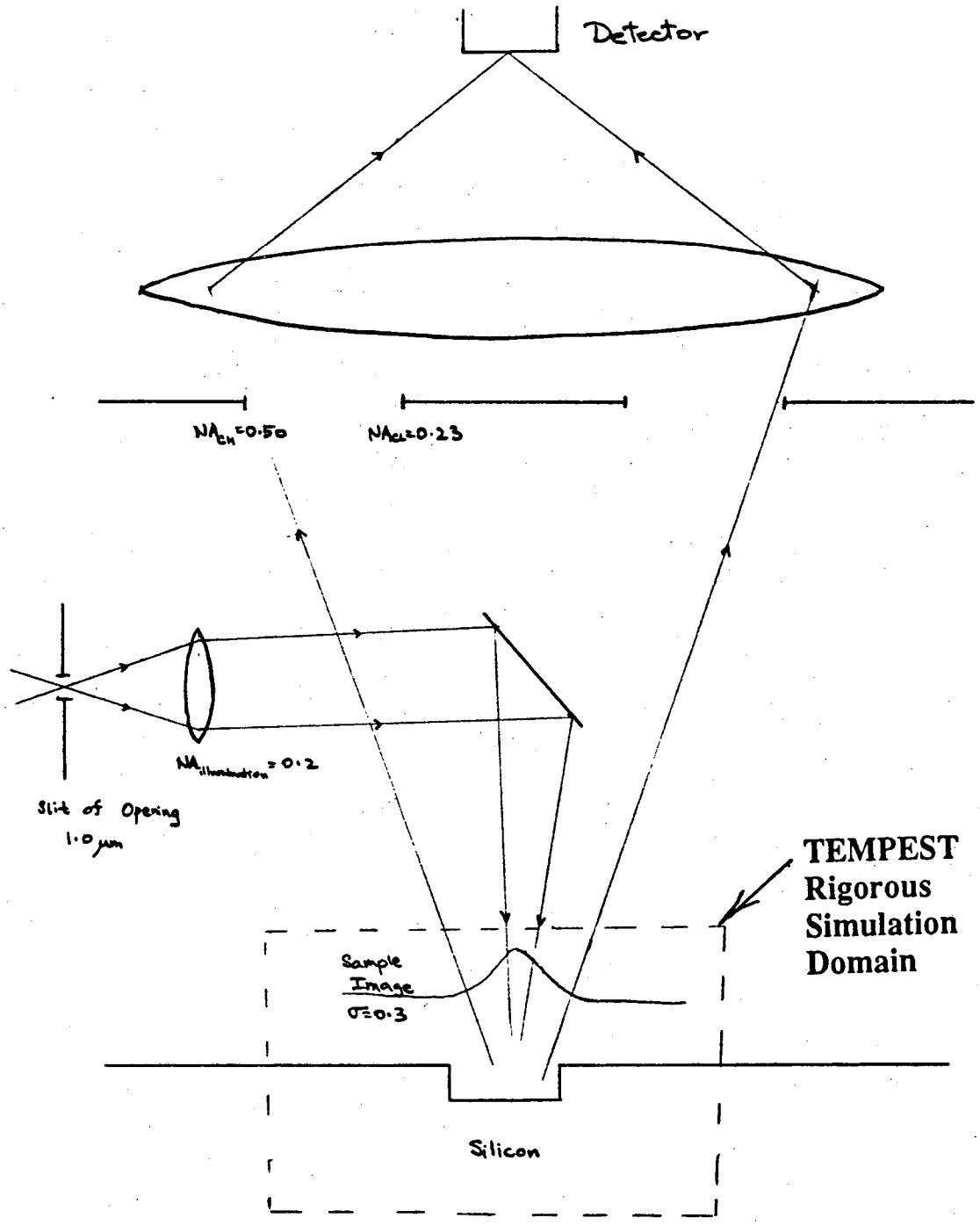








TEMPEST Link to Alignment Optics



Model Used in Analysis of Alignment Signals

3D Ray Trace and String Algorithms

In each case, surface is described by nodes, segments, and triangles.

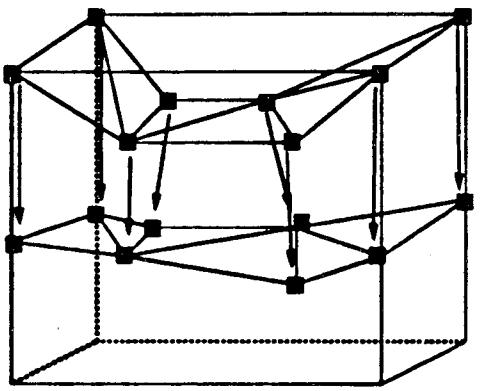
Difference is in how isotropic direction is calculated.

Ray Trace:

Vector is calculated from gradient of local etch rates.

$$\frac{d}{ds} n \frac{dr}{ds} = \nabla n$$

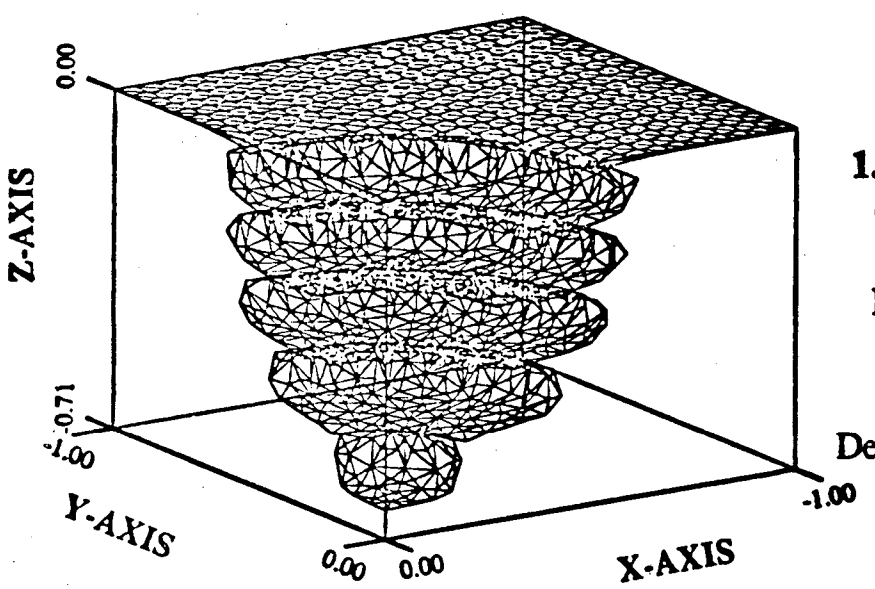
$$n(x,y,z) = \frac{R_{max}}{R(x,y,z)}$$



String:

Vector at point is sum of normal vectors of triangles at that point

Simulation of 3D Resist Development

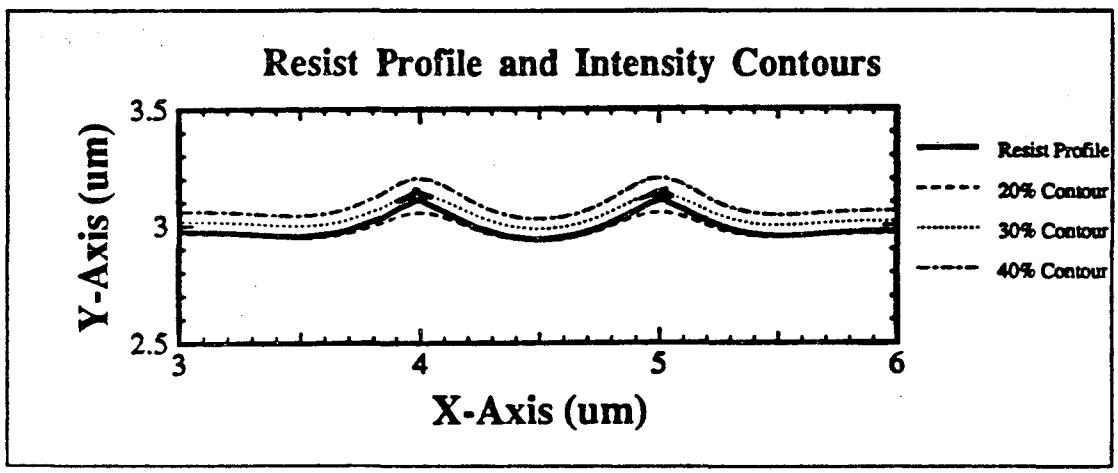


1.0 μm × 1.0 μm Contact Hole

Resist Surface After 15 sec Development Time

1 μm (0.64 λ/NA) Phase-Shifted Lines

Shipley 1470 : Dev. Time = 10 sec, Dose = 80 mJ/cm^2



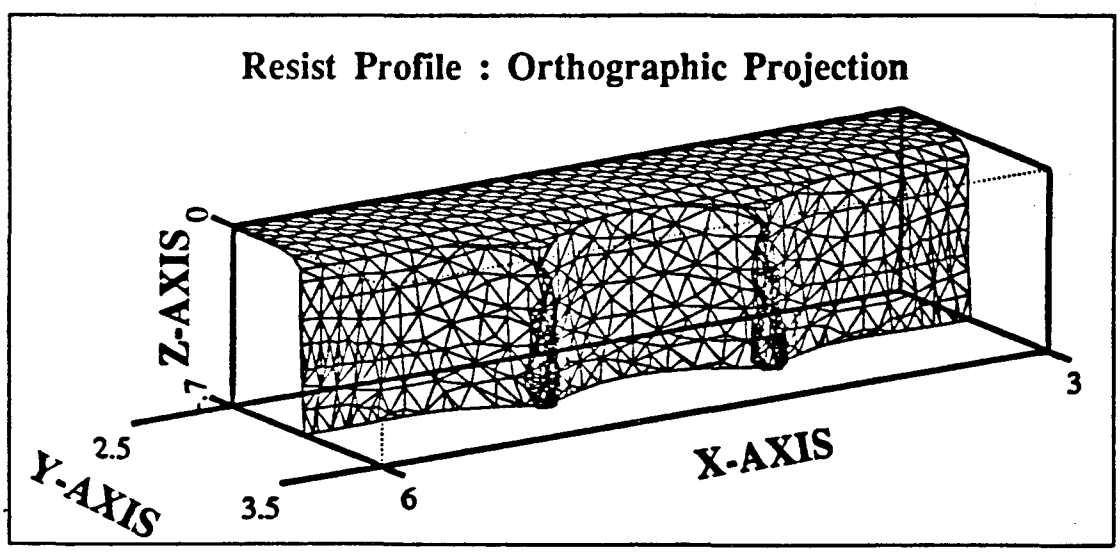
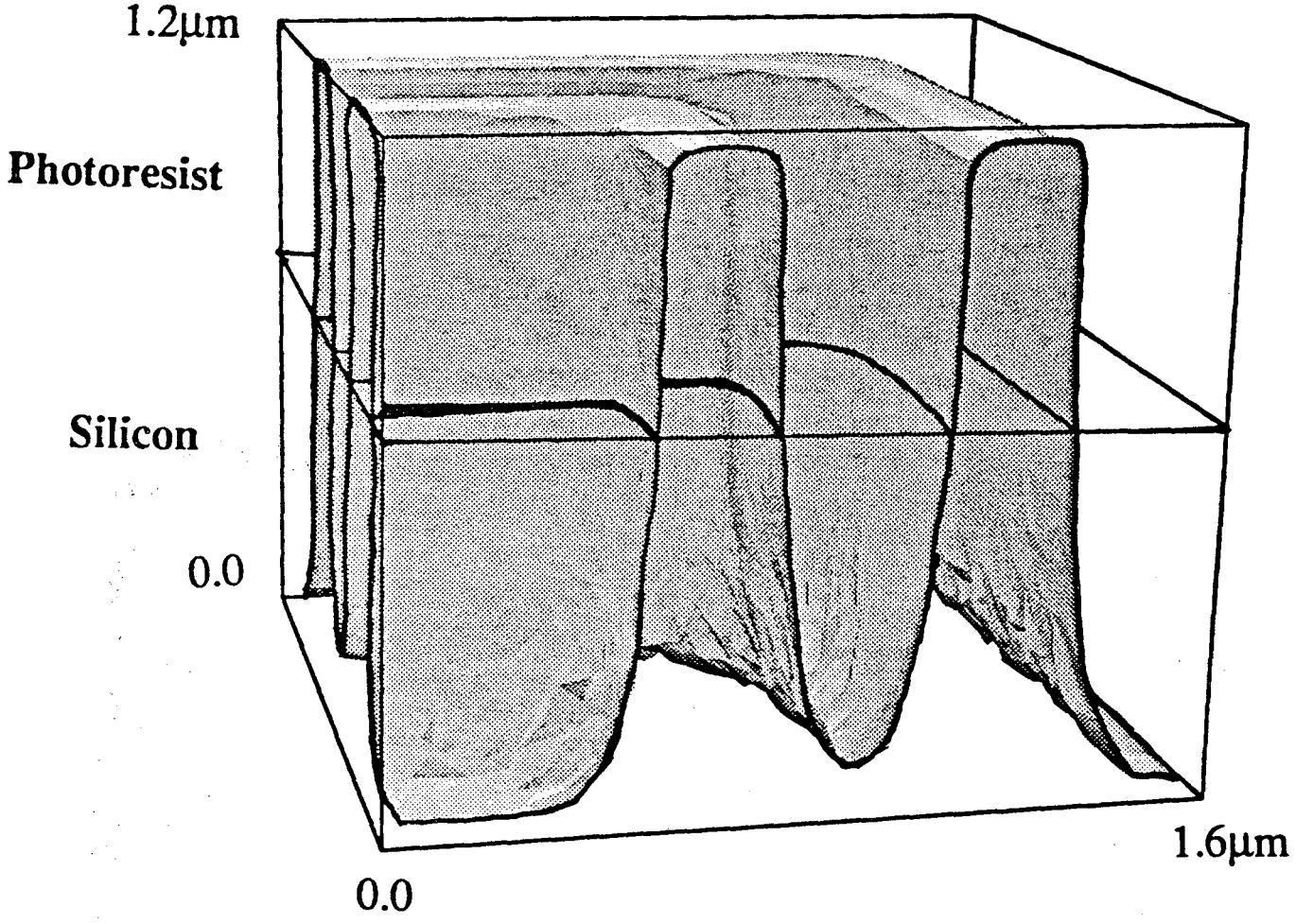


Figure 9.21 : 3D Resist Development, simulated on 0.7 μm of Shipley 1470 positive resist with 0.08 μm of post-exposure bake diffusion.


1.2μm
Photoresist
Silicon
0.0
0.0
1.6μm

SIMPL-IPX User's Manual

SIMPL-DIX 2.0
SIMPL-2 3.0

22 January 1990

by

The UC-Berkeley SIMPL Group

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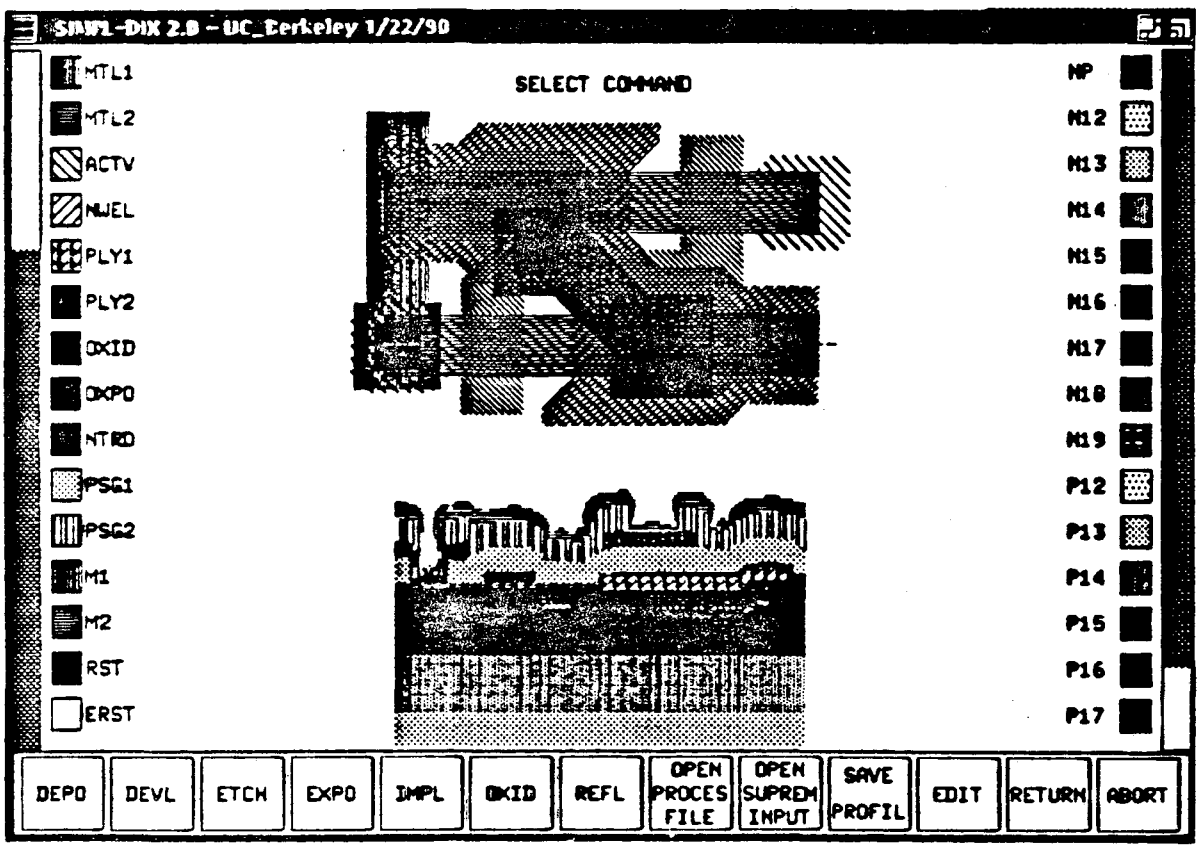

SUMMARY

- Very Strong Carry Over from Optical Lithography

- Lithographic Materials Characterization
  Measurement and Data Reduction Available
  Similarity Between X-ray and Electron-Beam
  Multi-State Modeling and Simulation Available

- Surface Imaging Techniques
  Chemically Based - Interesting Alternative
  Simulation Feasible

- Optical Imaging and EM Scattering
  Assessment of 2-D Images (Aberrations) - Available
  Scattering X-ray Mask Edges and Defects - Feasible

- 3-D Lithography Simulation
  2-D Imaging and 3-D Dissolution - Available
  3-D Pattern Transfer - Available

- TCAD Environments
  Lithography in Context of Complete Process
  Commercial Systems - Possibly Available

INDUSTRIAL PERSPECTIVES ON X-RAY LITHOGRAPHY

John Carruthers

Intel Corporation

INDUSTRIAL PERSPECTIVES ON ADVANCED LITHOGRAPHY

- CURRENT LITHOGRAPHY ROADMAP
- LITHOGRAPHY ISSUES
- POSSIBLE COLLABORATIVE RESEARCH OPPORTUNITIES

LITHOGRAPHY ROADMAP

Critical Dimension (micron)	Shrink %	Manuf. DRAM	Date Logic	Wavelength	NA	Field Size mm	Lithography Technology Resist	Mask	Dev/ Etch	Metrology
1.0	17	1985	1987	G-line	0.3	10 x 10	N	C	W	SEM
0.8	20	1988	1990	G-line	0.6	12 x 12	N	C	W	SEM
0.6	25	1991	1993	G/I-line	0.6/0-45	15 x 15	S	C/P	D	SEM
0.4	33	1994	1996	I-line/ 248mm	0.6/0.4	20 x 20	S/A	P	D/W	?
0.25	37	1997	1999	248/192	0.6/0.4	25 x 25	?	P	D/W	?
0.15	40	2000	2002	XUV/	?	30 x 30	?	R/T	?	?

Resists

N = Novolac

S = Surface Imaging

A = Chemical Amplification

Masks

C = Chrome/glass

P = Phase shift

R = Reflective Reduction

T = Transmission Reduction

Develop/Etch

W = Wet

D = Plasma etch

LITHOGRAPHY COST ISSUES

- NUMBER OF MASK LAYERS INCREASING FROM GENERATION TO GENERATION

- CAPITAL INVESTMENT INCREASING EXPONENTIALLY

- MATERIALS COSTS (RESISTS,MASKS) INCREASING EXPONENTIALLY

- MAJOR NEW PROCESSING STEPS WILL BE ADDED TO PATTERN TRANSFER

  - PLASMA ETCHING

  - RESIST PROCESSING

- METROLOGY COSTS ESCALATING WITH DATA INCREASES AND TOOL DEVELOPMENT NEEDS

- TOTAL COST INCREASES WILL NUCLEATE OTHER SOLUTIONS TO ACHIEVING INCREASED SYSTEM PERFORMANCE

  - TECHNICAL APPROACHES

  - ARCHITECTURAL APPROACHES

LITHOGRAPHY TECHNOLOGY ISSUES

- HIGHER NA'S RESULT IN DECREASING DEPTH OF FOCUS
  - LIMITS OF PROCESS PLANARIZATION
  - LIMITS OF SURFACE IMAGING
- FIELD SIZE INCREASE IS INEVITABLE
- CURRENT G-LINE AND I-LINE SYSTEMS BEING EXTENDED
  - SURFACE IMAGING RESISTS
  - FLEX
  - PHASE SHIFTED MASKS

  (FIRST FULLY FUNCTIONAL 64MG DRAMS @ 0.4 MICRONS BEING REPORTED AT ISSCC 91 USE PHASE SHIFTED I-LINE)
- METROLOGY IS ACHILLES HEEL
- XUV CAPABILITIES (1-100NM) ARE REVOLUTIONARY DEPARTURES
  - REFLECTION OPTICS VUV
  - PROJECTION/REDUCTION X-RAY
  - SOURCES, MASKS, RESISTS ALL NEW
  - LAYER-LAYER ALIGNMENT NEW

POSSIBLE COLLABORATIVE RESEARCH OPPORTUNITIES

- ANY XUV LITHOGRAPHY RESEARCH PROGRAM NEEDS TO BE ORGANIZED HOLISTICALLY:
  - SOURCE DEVELOPMENT
  - PHYSICAL OPTICS DEVELOPMENT
  - PATTERN TRANSFER DEVELOPMENT
  - METROLOGY DEVELOPMENT
- NEW CONCEPTS SHOULD BE ACTIVELY PURSUED IN THIS ENVIRONMENT

EG
  - NON-SCHWARZCHILD REFLECTIVE OPTICS
  - MASK AS AN OPTICAL ELEMENT
  - OPTICAL COMPUTING FOR MASK INSPECTION
  - EXPOSURE/ETCH IN ONE STEP
  - METROLOGY TEST STRUCTURES
  - ETC.
- NATIONAL LABORATORY LEADERSHIP IS VITAL TO OUR LONG TERM SUCCESS

WORKSHOP OBJECTIVES

- UNDERSTAND CURRENT STATUS OF X-RAY LITHOGRAPHY
- UNDERSTAND CAPABILITIES OF ALS
- UNDERSTAND INDUSTRIAL AND RESEARCH NEEDS IN ADVANCED OPTICAL LITHOGRAPHY
- EXPLORE OPPORTUNITIES FOR ADVANCING STATE OF ART USING LBL AND LLNL CAPABILITIES

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