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Author
Attwood, D.T.

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Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Center for X-Ray Optics

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D. Attwood

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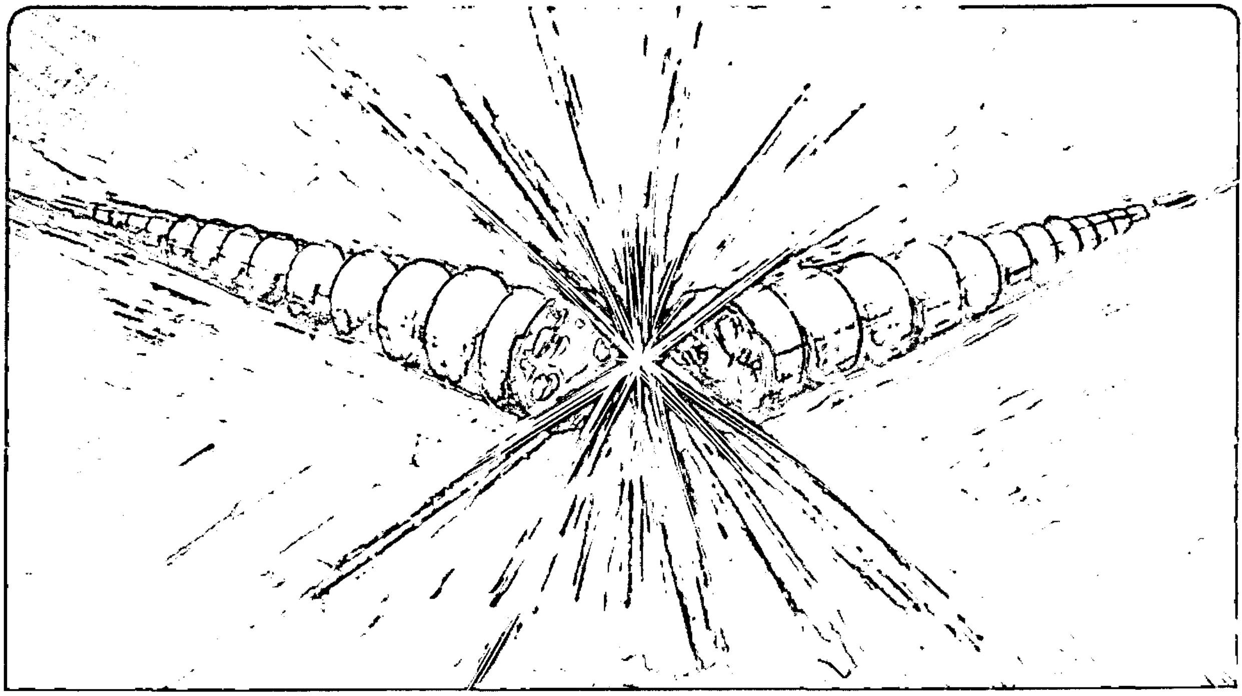

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CHALLENGES FOR UTILIZATION OF THE NEW SYNCHROTRON FACILITIES

David Attwood
Center for X-ray Optics
Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
One Cyclotron Road
Berkeley, CA 94720

Introduction

The emergence of third generation synchrotron radiation facilities provides new scientific opportunities and challenges. Optimized for small phase space ("emittance") electron beams, long periodic magnet structures, and dedicated scientific user access – these new machines promise significant increases in spectral brightness, as well as enhanced spatial and temporal coherence properties, which translates to new opportunities for combining high spatial and spectral resolution. The challenges to the machine builders are well known: designing and maintaining the small phase space beams, constructing long magnet structures with minimal errors, stabilizing the beam to long and short term fluctuations, and multiple undulator tuning, to name a few.

The challenges in beamline optics, spectroscopic and focusing systems are also quite clear. The issue of optical stability quickly comes to the forefront as we attempt to focus and image to ever finer spatial scales, with minimal loss of photon flux. Surface figure and polish are of greater importance, as is minimization of aberrations, as we strive to maintain these small phase space photon beams. The higher intensities and power loading mandate cooled, or cleverly controlled optics, to avoid thermal distortion. Spectroscopic efficiency, with minimal wavefront distortion to the near diffraction limited radiation, becomes more important, as do order and harmonic suppression in the design of monochromators and spectrometers. Focusing systems of higher spatial resolution are called for – with both diffractive and reflective optics. Single pulse and sub-pulse time resolving experiments, as well as two-color pump-probe experiments are likely to play a far greater role.

Two of our major issues will be efficient time sharing of these valuable resources, relegating time consuming setup procedures to branch lines while others take data, and controlling the cost of these ever more complex beamline engineering systems.

Third Generation Synchrotron Facilities

Third generation synchrotron facilities are those which are not only designed for dedicated experimentation by photon users (2nd generation), but are also optimized for high brightness radiation based on small phase-space* electron beams traversing long periodic magnet structures (see figure 1). Two complimentary facilities are under construction in the United States, the 1.5 GeV Advance Light Source (ALS) in Berkeley which is optimized for high spectral brightness and partial coherence at soft x-ray and vacuum ultraviolet wavelengths, and the 7 GeV Advanced Photon Source (APS) at Argonne National Laboratory, which is optimized for high brightness in the hard x-ray region of the spectrum. Other facilities are in various stages of planning and construction in at least a half a dozen countries around the world. Examples of spectral brightness and partial coherence anticipated at facilities in the United States are shown in figure 2. Coherent power is taken, somewhat arbitrarily, as that portion of the radiation which is diffraction limited and characterized by a one micron coherence length. Table 1 lists some of the common photon parameters relevant to third generation performance.

Challenges to the Machine Builders

The achievement of orders of magnitude increases in spectral brightness and coherent power at x-ray wavelengths provides technical challenges for the accelerator physicists and engineers who must design and build the storage ring and magnet structures. In addition they have the significant burden of assuring stabilization of the beam position and trajectory to degrees far in

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* Phase space is a term which refers to the product of spatial size and angular divergence.

excess of that previously required with present day, larger phase-space electron beams. Although undulators have been retrofitted to some existing rings, they have seen limited tuning. The new machines have a great challenge ahead as they attempt to isolate the effects of tuning between various magnet structures as different experimental teams attempt to simultaneously explore spectral signatures at their individual end stations. Figure 3, which illustrates differences between present and third generation facilities, shows how short and long period magnet structures will provide differing spectral coverage on the same storage ring. With various users operating simultaneously there is also the challenge to machine builders to provide a mechanism whereby single bunch operation is possible at one or more stations, while continuing to provide multibunch operation (maximum photon flux) to all other users around the ring. Table 2 summarizes these technical challenges to the machine builders.

A particularly important challenge to machine builders and beamline designers as well, is that of electron and photon beam stabilization for which, important work is already underway[1,2]. Table 3 outlines a multilevel approach to beam stability due primarily to T. Warwick and his colleagues[3]. This approach requires thermal stabilization of significant portions of the facility to both long term and short term fluctuations, photon beam monitors to provide feedback to the electron beam at each insertion device, and subsequent stabilization of the photon beam position and angle through the beamline optics to the end station and final focusing optics. Requiring one-tenth rms size and divergence of the ALS electron beam, for example, is quite a challenge, as indicated in table 4.

Challenges for Beamline Engineering

The challenges in beamline engineering are more critical for these third generation facilities than with previous facilities. Having achieved small phase electron beams, radiating near diffraction limited x-rays, it is quite a challenge to design a beamline optical system – including monochromator or spectrometer, and focusing elements – that do not aberrate the beam and thus destroy the small phase-space attributes of brightness and coherence. Because of the high photon beam intensities and power loading, this will require not only clever optical designs, but also thermally protected components, designed and built in a cost effective manner. Table 5 delineates some of these issues. Note that again stability is a major issue for beamline designers, as illustrated in figure 4, which attempts to convey the additional challenges imposed by smaller phase-space radiation. The reference to time-effective designs in table 5 refers to the need for branchlines and other time sharing techniques so that valuable photons are not wasted during set-up time or other beamline activities.

Conserving brightness in an optical system is an issue and challenge that requires special attention. Table 6 outlines a few thoughts on this matter. With the new facilities it becomes critical to design beamlines that do not diminish brightness through aberrations associated with component shape and imaging properties, nor through contour distortions or microroughness associated with optical surface preparation and polishing. P. Takacs has established an optical surface characterization capability at Brookhaven for measuring spatial frequencies of surface height over a broad range, extending from microns to centimeters[4]. An example of his data, and the effect of roughness on surface reflections is shown in figure 5. The ability to not only specify desired surfaces to some mathematical certainty, but also to polish microroughness without incurring contour deformation[5], and then accurately characterize resultant real surfaces so as to provide feedback to the preparation process, will be crucial to the success of these new programs.

Figure 6 shows a sequence of relevant developments relating to minimizing thermal distortion in thermally loaded optical elements subject to spatially localized high power x-ray beams, an effort at LBL led for several years by M. Howells. Figure 6a shows a finite element model for the numerical design and study of thermally loaded x-ray optical surfaces[6]. Figure 6b shows a water-cooled VUV grating designed and built by McKinney, Lauritzen and colleagues[7] at LBL for use with the beamline 6 wiggler at Stanford's SSRL, and figure 6c shows a view of the water cooled mirror the group designed and installed on the X-1 undulator line at Brookhaven's NSLS[8].

Instrumentation Challenges

Describing instrumentation challenges at modern synchrotron facilities is a challenge in itself due to the wide diversity of experimentation that goes on there. Table 7 provides a partial list of instrumentation challenges particularly relevant to the new facilities. With such a high premium (facility cost) being paid for high spectral brightness and near diffraction limited wavefronts, it is essential that spectrometer/monochromator designs consider not only achievable spectral resolution and throughput[9], but also such considerations as minimization of wavefront distortion (will the monochromator and associated optics impede focusability?), and the suppression of undesired undulator harmonics and diffraction orders.

With facilities built to permit new scientific opportunities, based on high spatial resolution microprobe and focusing optics, it is essential that the state-of-the-art in both diffractive and reflective imaging optics continue to be pushed. For the immediate future that may mean achieving 300Å spatial resolution with soft x-ray zone plates[10], and 1 micron resolution with a multilayer coated hard x-ray microprobe[11]. As these facilities turn on, it would be more satisfying to see soft x-ray probing of material surfaces and wet biological structures spatially resolved to 100Å, and a hard x-ray microprobe for materials research approaching full photon flux to a 0.1 micron spatial resolution, perhaps with tomographic capabilities.

Multilayer optics may help in several ways. In addition to high reflectivity and wavelength selectivity, they can also help to reduce aberrations in reflective optic systems because the angles of incidence are generally closer to the optical axis. They are also thermally robust and thus may be utilized in various situations, to protect more delicate optics, to suppress unwanted orders and harmonics, to provide a 90° turn so that biological and other gravity sensitive samples may be mounted horizontally, and perhaps to provide an inexpensive route to polarization control of radiation from a single linear undulator[12].

Detection capabilities matched to our widely varied interest and applications are too diverse to review in a short paper. In addition to covering the spectrum from ten eV to tens of keV, we are interested in efficiency, array size, pixel size, time response, positional sensitivity, ease of readout, etc. This is a difficult task and must be considered as part of the broad but specialized efforts of many communities similar to, and perhaps overlapping with our own synchrotron community.

Effective Time Sharing

Perhaps the greatest challenges of all are associated with the sociological constructs that will be required to achieve effective time sharing of very valuable photons. (See Table 8) After careful spectroscopic sculpting, spatial trimming, and delivery to our carefully prepared sample chambers the question will arise – "what is a fair share"? These facilities are the result of a great investment, of order one billion dollars, and our very precious professional careers. The very expensive photons and cherished personal efforts and goals must not be wasted. Branchline splittings are essential for efficient use of the facility. While one group is setting up complex experiments, another should have access to the beam. Alignment of optics and pre-focus procedures should be done off-line – not while taking beam. If special facilities, ultrahigh vacuum chambers for instance, need to be protected, alternate chambers or branchlines must provide access and utilization for non-specialists and other non-participants. For national facilities such as these – indeed national treasures where new science and new technology will flourish – sharing will be essential and user friendliness the only route to effective utilization. We must bear in mind the privileged access we have to a very substantial national investment.

Acknowledgements

Conversations with many colleagues at LBL, NSLS, SSRL and SRC are gratefully acknowledged. In particular I wish to acknowledge very valuable discussions with Tony Warwick of LBL, who is engaged in addressing the issues of stability and thermal stabilization at the ALS, a most critical issue for us at this stage of our technical evolution. This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Fig. 1. Bright, partially coherent x-rays are generated across a broad spectral region by relativistic electrons traversing long periodic magnet structures.

Fig. 2. The new synchrotron radiation facilities promise significant advances in brightness and coherent power at x-ray wavelengths.

Fig. 3. The evolution of synchrotron radiation facilities is towards storage rings comprised of many straight sections for periodic magnet structures which generate differing wavelengths of "laser-like" (partially coherent) radiation and which utilize tightly controlled electron beams of small spatial size and angular divergence.

Fig. 4. Stability of imaging and spectroscopic systems becomes a critically important issue in third generation facilities.

Fig. 5. The preparation of contoured surfaces, polished to minimize surface microroughness without introducing larger scale distortions is a critical issue in maintaining high brightness radiation as it is transported through the beamline optical system to the sample chamber. The above illustrates work on surface characterization over a broad range of spatial frequencies (P. Takacs, Brookhaven National Laboratory).

Fig. 6. (a) Finite element numerical modelling techniques are necessary for analyzing and predicting the performance of water cooled, thermally loaded x-ray optical components (R. DiGennaro and T. Swain, LBL); (b) Water cooled gratings for the XUV have been developed and tested on Stanford's 54 pole wiggler (W. McKinney, et al, LBL); (c) Water-cooled x-ray Mirror has been built and tested on the X-1 undulator beamline at Brookhaven's National Synchrotron Light Source (R. DiGennaro and M. Howells, LBL).

Table 1

Some Terminology

Photon Flux	$\mathfrak{F} = \text{photons/sec}$
Brightness	$B = \frac{\text{photons/sec}}{\Delta A \cdot \Delta\Omega}$
Spectral Brightness	$SB = \frac{\text{photons/sec}}{\Delta A \cdot \Delta\Omega \cdot \left(\frac{\Delta\lambda}{\lambda}\right)}$
Power	$P_T = h\nu \cdot \text{photons/sec} = SB \cdot \underbrace{\Delta A \cdot \Delta\Omega}_{\pi^2(d\cdot\theta)^2} \cdot \frac{\Delta\lambda}{\lambda^2} \cdot hc$
Coherent Power*	$P_{coh} = \frac{\left(\frac{\lambda}{2}\right)^2 SB\cdot hc}{\ell_{coh}}$ when $\Delta A\cdot\Delta\Omega \to \lambda^2/4$
Coherent Power*	$P_{coh} = P_T \cdot \frac{\lambda^2/(2\pi)^2}{(\text{phase space})^2}$

*$d\cdot\theta = \frac{\lambda}{2\pi}$ for Gaussian rms measures

XBL 896-6249

Table 2

Technical Challenges for the Machine Builders

- Designing and maintaining small phase-space electron beams
- Constructing long magnet structures with minimal errors
- Stabilizing the beam to long and short term fluctuations
- Mulitiple undulator tuning
- Simultaneous single bunch/multibunch operation

Table 3

A Multilevel Approach to Beam Stabilization

(T. Warwick/ALS)

- Beam monitors and feedback to stabilize the electron beam within the ring
- Temperature control of portions of the facility, and of the cooling water
- Photon beam monitors (2) for feedback to the electron beam at each insertion device
- Stabilization of the photon beam position and angle

Table 4

Beam Stability Requirements are Stringent

(T. Warwick/ALS)

- **One-tenth rms size/divergence of photon beam**
- **ALS electron beam:**

	beam size/divergence (σ)	stability requirement ($\sigma/10$)
σ_h	330 μm	33 μm
σ_h'	30 μr	3 μr
σ_v	63 μm	6 μm
σ_v'	16 μr	1.6 μr

Table 5

Technical Challenges for Beamline Engineering

- Phase-space conserving beamline optics
- Stable beamline optical systems
- Thermally protected optical systems
- Cost effective designs
- Time effective designs

Table 6

Conserving Brightness in an Optical System

Brightness is conserved in a <u>perfect</u> optical system

- Aberrations diminish brightness
- Contour distortions and roughness also diminsh brightness

These provide challenges in the areas of

- Optical design
- Surface characterization
- Polishing proceedures

Table 7

Instrumentation Challenges – A Few Examples

- High resolution spectrometers/monochromators, which minimize wavefront distortion, suppress unwanted orders, and minimize cost.
- Efficient, high resolution diffractive and reflective imaging optics
- Detection capabilities matched to our varied applications (efficiency, array size, pixel size, time response, position sensitive,...)
- Polarization control and sensitivity

Table 8

Effective Time Sharing of Beamline Photons

- A great investment is being made ($B, and our careers)
- Expensive photons should not be wasted
- Branchline splittings are essential for complex experiments
- Facility sharing will be essential
- User friendly is not a joke – it too is essential

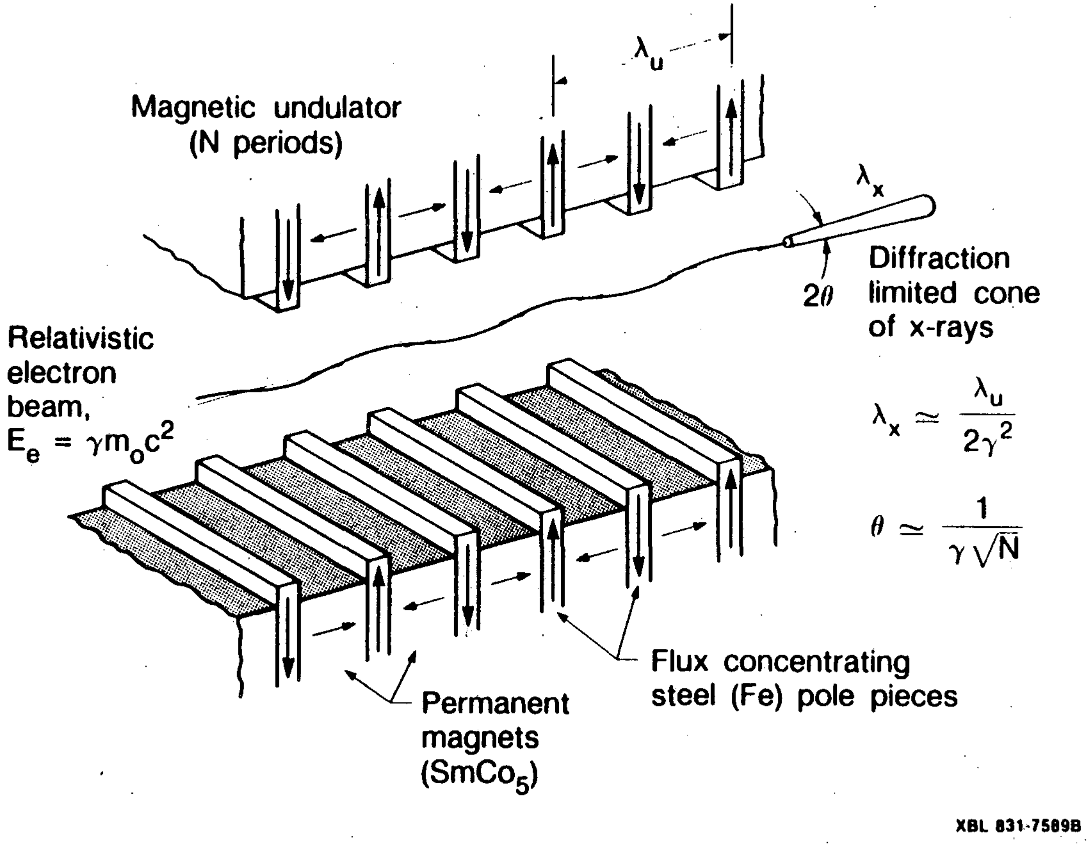
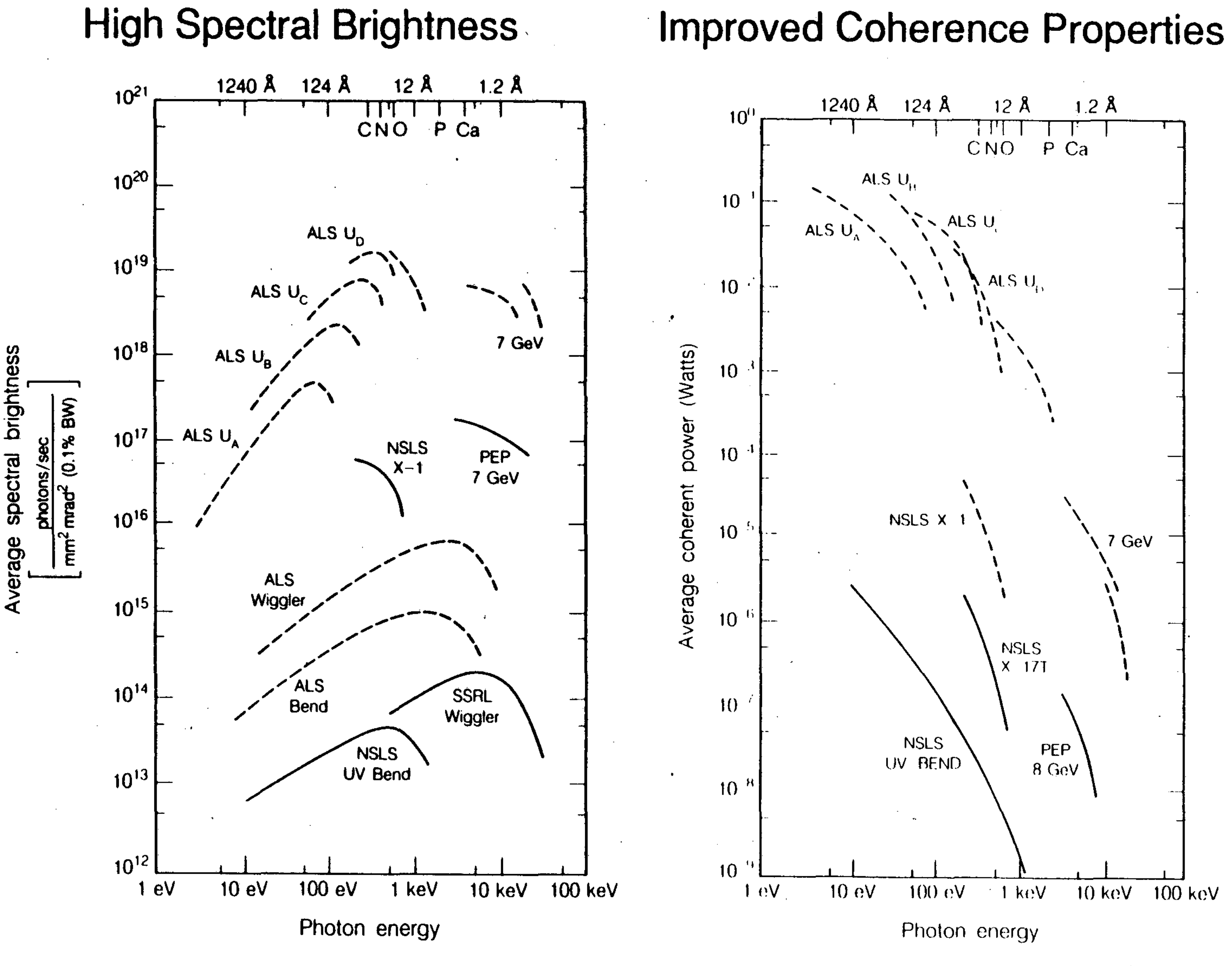

Magnetic undulator
(N periods)
λ_u
λ_x
2θ
Diffraction limited cone of x-rays
Relativistic electron beam, $E_e = \gamma m_o c^2$
$\lambda_x \simeq \frac{\lambda_u}{2\gamma^2}$
$\theta \simeq \frac{1}{\gamma\sqrt{N}}$
Flux concentrating steel (Fe) pole pieces
Permanent magnets ($SmCo_5$)
XBL 831-7589B

Figure 1



High Spectral Brightness

Improved Coherence Properties

Figure 2

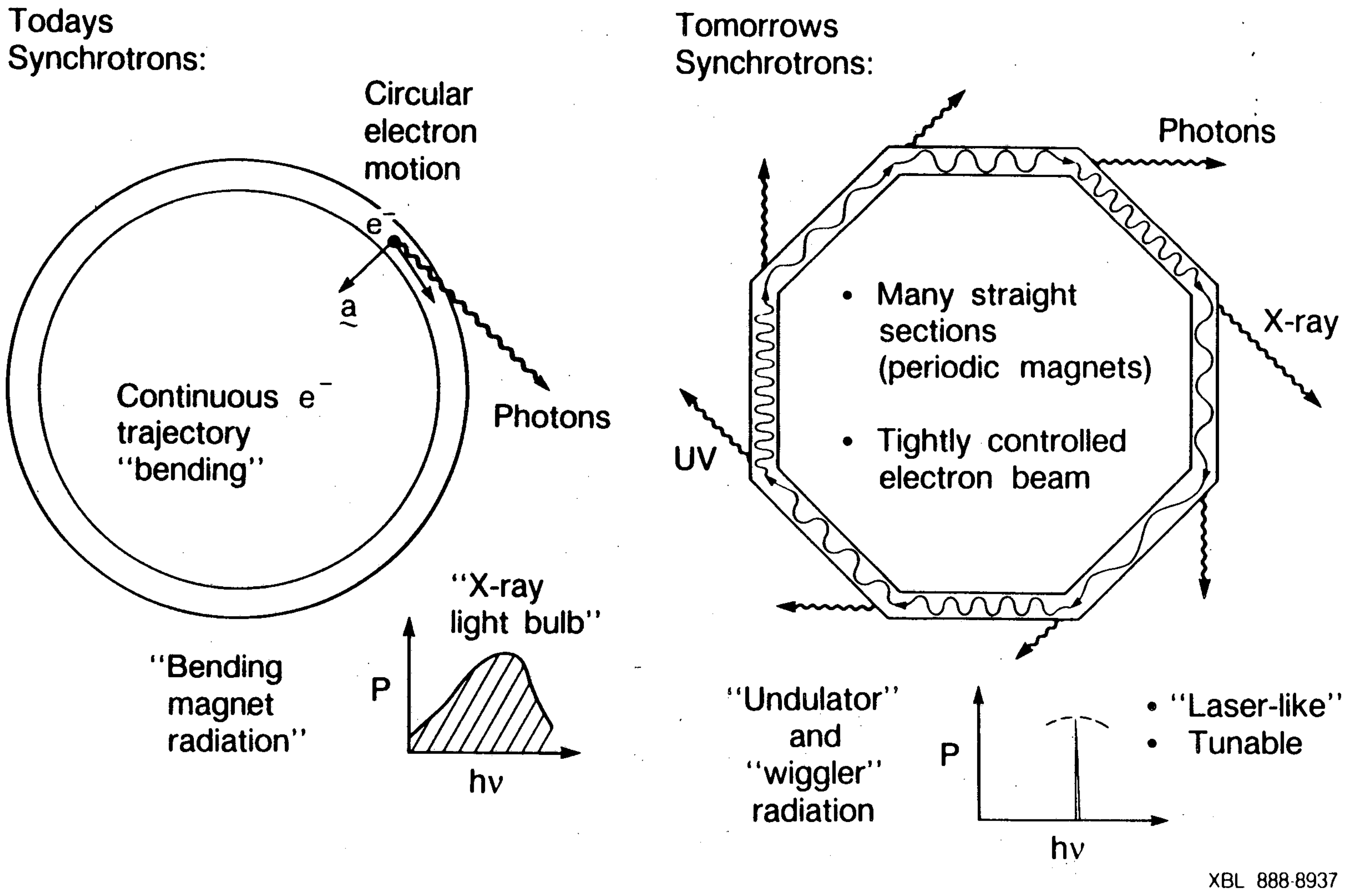
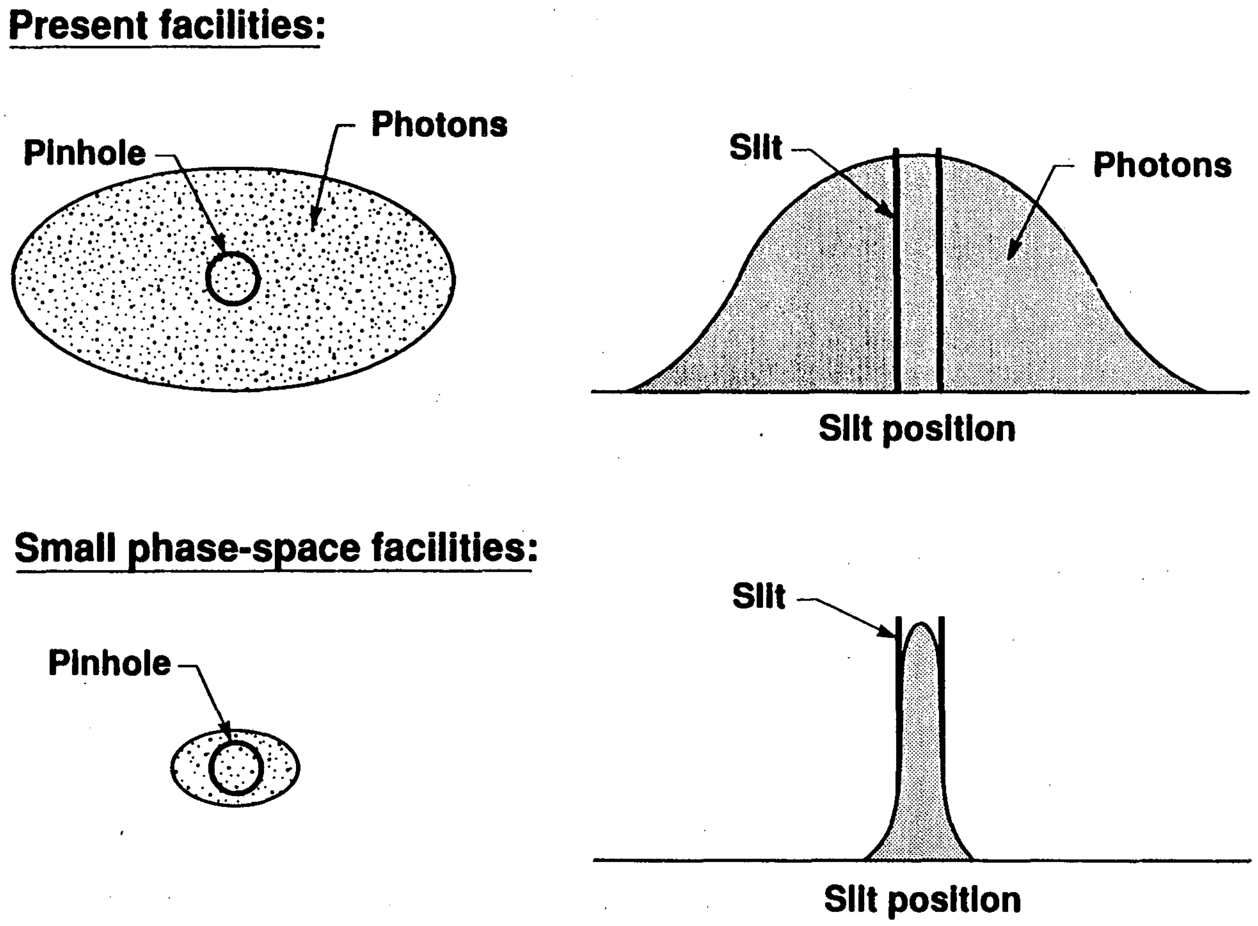

Todays Synchrotrons:
Circular electron motion
e^-
$\underset{\sim}{a}$
Photons
Continuous e^- trajectory "bending"
"X-ray light bulb"
"Bending magnet radiation"
P
hν
Tomorrows Synchrotrons:
Photons
• Many straight sections (periodic magnets)
• Tightly controlled electron beam
X-ray
UV
"Undulator" and "wiggler" radiation
P
hν
• "Laser-like"
• Tunable
XBL 888-8937

Figure 3



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TID/MAC/lg

Figure 4

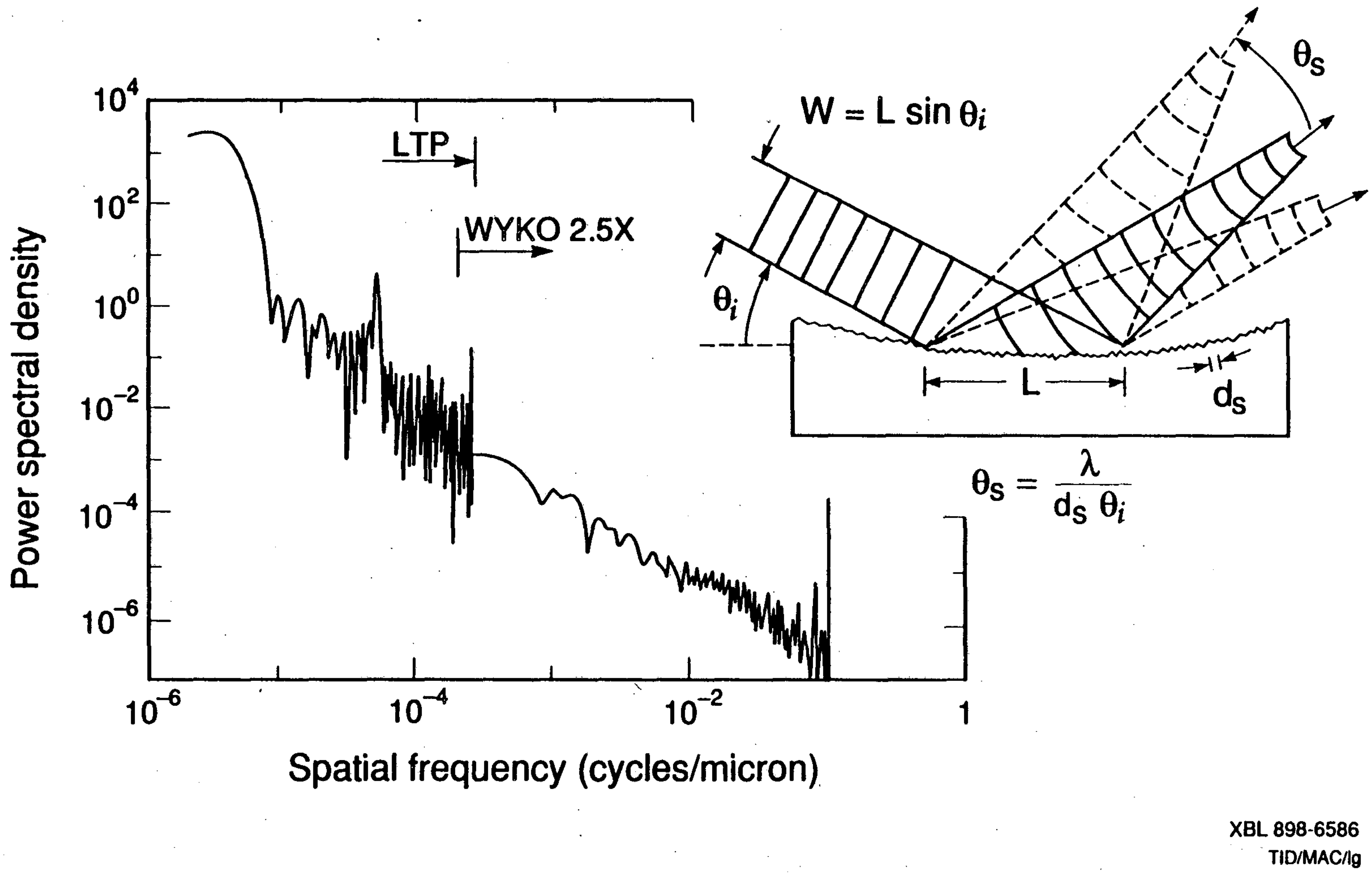
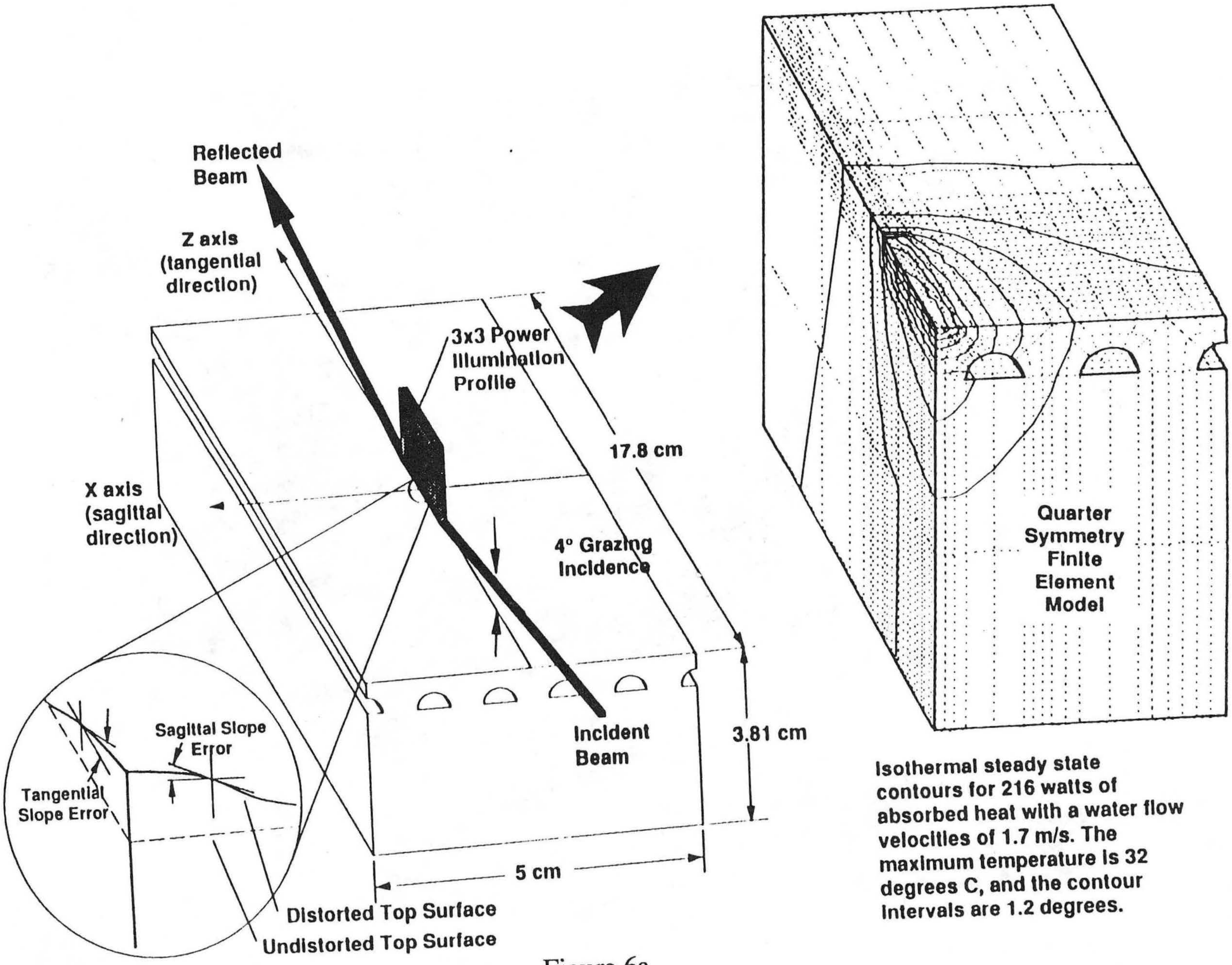

10^4
10^2
10^0
10^-2
10^-4
10^-6
Power spectral density
10^-6
10^-4
10^-2
1
Spatial frequency (cycles/micron)
LTP
WYKO 2.5X
W = L sin θi
θi
θs
L
ds
θs = λ / (ds θi)
XBL 898-6586
TID/MAC/lg

Figure 5



Isothermal steady state contours for 216 watts of absorbed heat with a water flow velocities of 1.7 m/s. The maximum temperature is 32 degrees C, and the contour intervals are 1.2 degrees.

Figure 6a

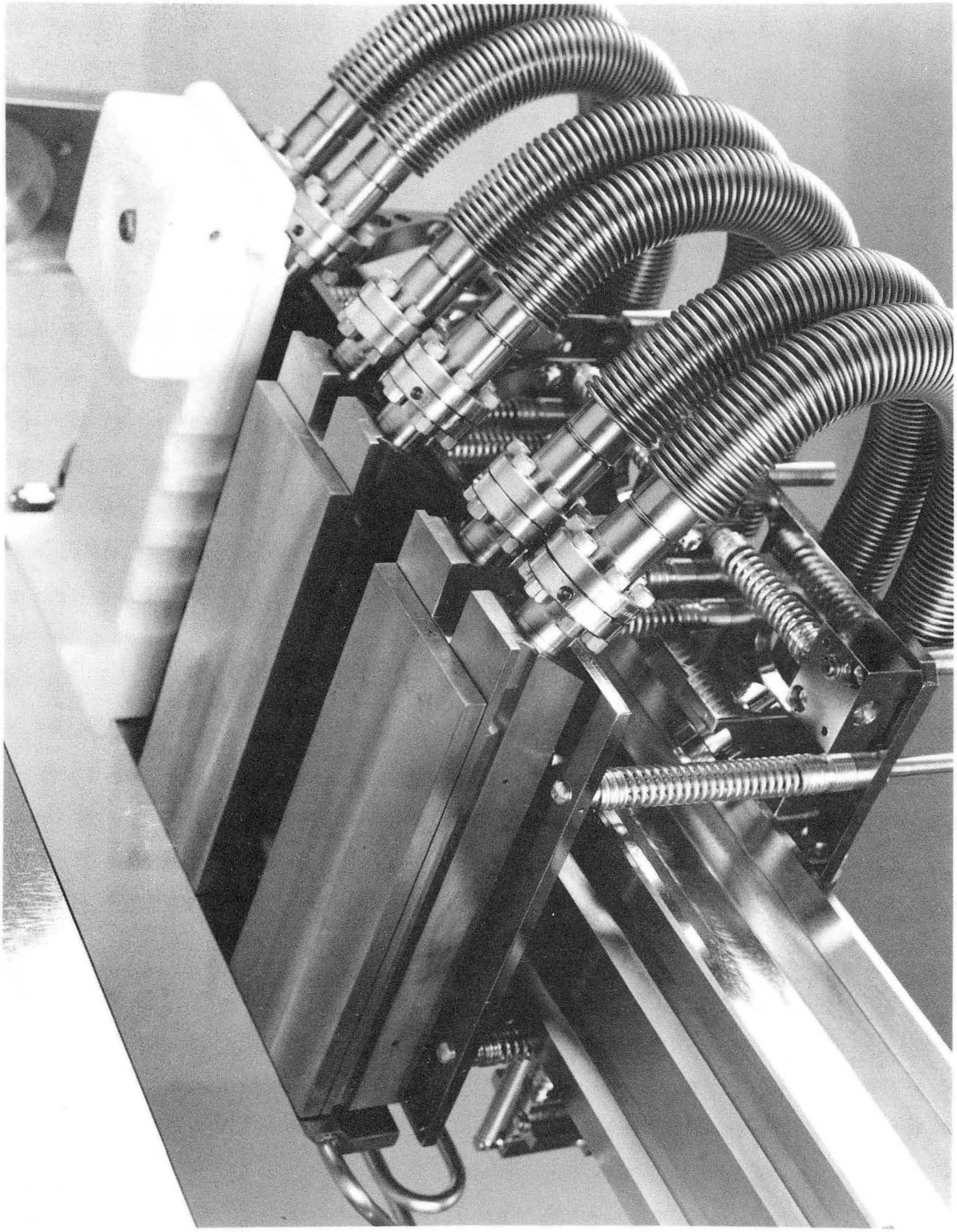


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Figure 6b

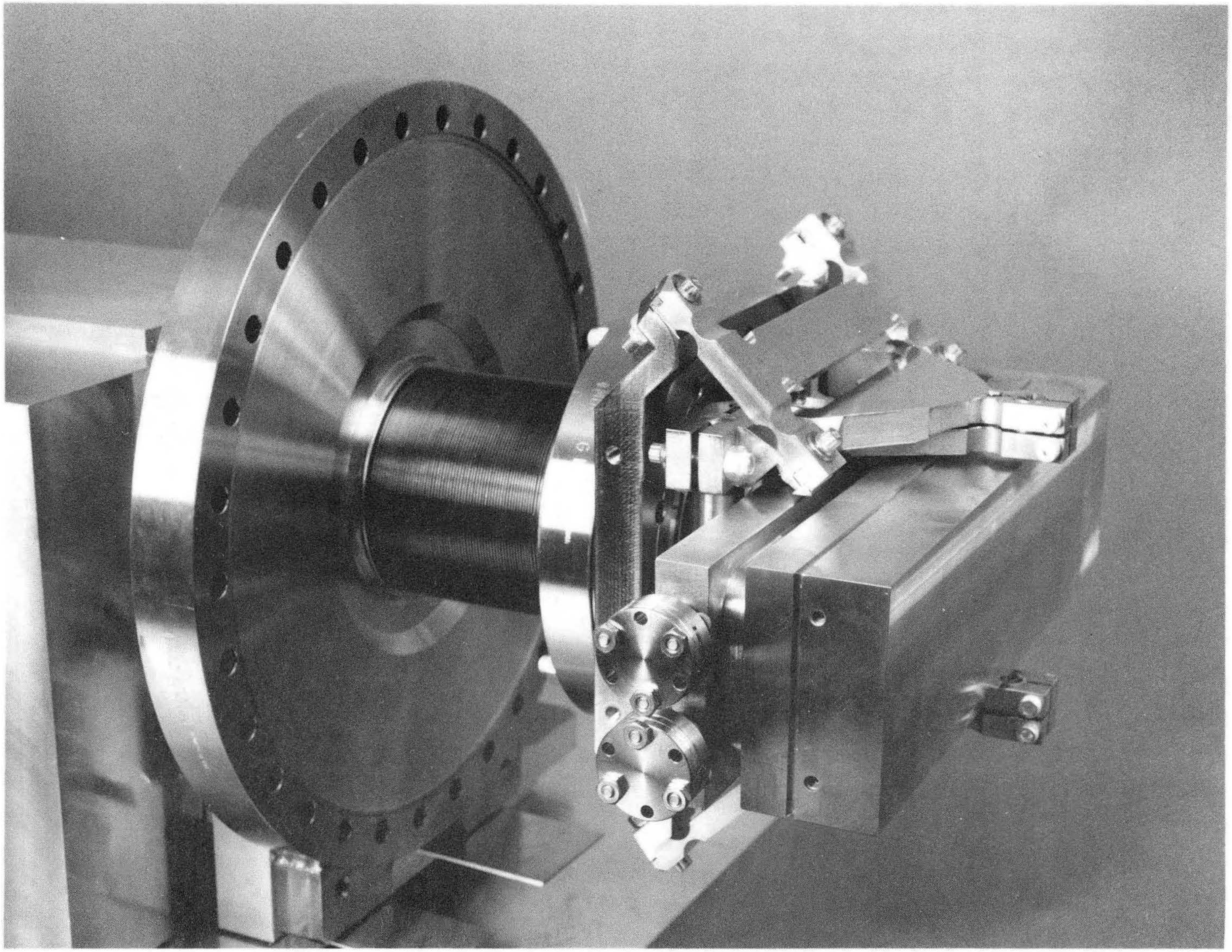

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Figure 6c

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