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SYNCHROTRON RADIATION

Characteristics, Instrumentation and Principles of Research Applications - an Introduction

by

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OUTLINE

Synchrotron Radiation, Characteristics, Instrumentation and Principles of Research Applications - an Introduction

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1.1 Synchrotron Radiation as a Scientific Tool

Observations and studies of the interaction of electromagnetic radiation with matter have provided us with much of our knowledge about the geometric and electronic structure of the world surrounding us. This has been evident for some time for the visible and x-ray regions of the radiation spectrum. In the past few decades, important developments in new sources of radiation have enabled us to extend spectroscopic methods into the nonvisible regions of the spectrum. These extensions into the ultraviolet and shorter wavelengths as well as into the infrared and beyond have broadened our views in many respects. Today, spectroscopic methods and photon-scattering experiments of a wide-ranging variety are indispensible tools for basic and applied research in physics, chemistry, biology and medicine.

The concept of electromagnetic waves as developed by Maxwell and others together with the elucidation of the quantum theory of radiation in our century has provided us with the knowledge needed both to generate radiation and to tailor its properties so as to obtain a maximum of useful information from each experiment. For example, spectroscopy in the visible region has been the experimental basis for quantum mechanics while infrared spectroscopy has provided detailed information of the geometrical properties of molecules. For studies of excited states of atoms, molecules and condensed matter, the energy of the radiation quanta must be matched to the excitation energies of these systems, while the geometrical structure of matter, even as complex as that of proteins, is well matched by the wavelengths of x-rays. Without exaggeration one can conclude that many new sources of radiation which have been developed have lead to important discoveries and advances in basic and applied science, and certainly synchrotron radiation (SR) is such a source (Fig. 1, Fig. 2).

Synchrotron radiation is produced when a fast charged particle with an energy $E \gg m_0 c^2$ is deflected in a strong magnetic field. Circular electron and positron accelerators - in particular storage rings - in which the particles move with relativistic energies, are the "natural" man-made sources of this radiation (Fig. 3, Fig. 4). In Figure 4 a SR source is schematically sketched. Electrons are injected into an electron synchrotron (Booster) at a relatively low energy, say several 100 MeV from a linear accelerator; in the synchrotron these electrons are accelerated on a fixed circular orbit. The synchrotron consists of an array of magnets for focusing and bending the beam and straight linear sections for accelerating the particles. The magnetic field in the deflecting magnets rises during the acceleration in order to keep the electrons on the same circular path when their energy is gradually increased. Finally, when they reach the appropriate energy, the electrons are transferred to the storage rings. Here the magnetic field remains constant. Accelerator sections within the storage ring compensate for the losses due to synchrotron radiation. Around the storage rings the radiation from the stored electrons can be used by various experiments.

For spectroscopy SR has a number of outstanding properties:

1. Intense continuum from the infrared out to the x-ray region.
2. High degree of collimation ($\sim$ 1 mrad).
3. Polarization, completely linear in the plane of orbit.
4. Time structure, pulse duration as short as 100 psec.
5. Quantitatively known characteristics.
6. High stability of storage rings.
7. Clean environment (10^{-9} Torr).

Thus, SR spans the large gap between the far UV and the x-ray range as well as being a unique x-ray source, and the unique combination of the above characteristics offers far reaching possibilities for many fields of science and technology.

Traditionally, the two most common techniques have been absorption and reflection spectroscopy in the IR, visible and UV, and diffraction in the x-ray range. Scattering, emitted fluorescence and electron emission by radiation may also be studied and have become widely practiced. For the latter experiments, the ability to study these processes using SR as a function of the excitation energy, which can be selected from the continuum by various types of monochromators, is a major advantage. Furthermore, there are a number of experiments which very elegantly can make use of the white continuum of SR.

We have summarized many of the widely-used spectroscopic techniques and their relation to scientific problems in the matrix appearing in Table I and in Fig. 2. In many areas of current research important contributions have been made by the use of SR as a light source. Among these are:

(i) Atomic and molecular spectroscopy of highly excited states including absorption, photoelectron and mass spectroscopy, as well as time-resolved spectroscopy.

(ii) Investigation of the energy band structure of solids and surfaces by means of angle-resolved photoelectron spectroscopy and of excitons; deep level spectroscopy.

(iii) X-ray absorption and x-ray scattering experiments for the investigation of the geometrical structure of crystalline and amorphous solids, dilute systems, and biological materials.

(iv) Use of SR for applied research in soft x-ray optics, soft x-ray microscopy, and x-ray lithography.

While the applications of SR are wide-ranging and not a homogeneous subject, there is no doubt that SR itself is a fascinating theme.

It is felt that there is much to be gained by bringing the diverse types and applications of research with synchrotron radiation together and to provide easy access, thus stimulating cross-fertilization of ideas and methods. There is no doubt that this large field will continue to expand and remain a major international scientific activity in the coming decade. This is due to the world-wide growth in facilities and their new capabilities as well as to the large and diverse body of researchers interested in using this radiation for their research projects.

In the present chapter we give a qualitative introduction to the field by addressing simple questions such as, what is synchrotron radiation, what is the historic development which led to the present worldwide interest, what is the status of SR sources and how do they compare with other sources, and what are the major areas of activities at present and in the foreseeable future. These questions are discussed in depth in the following chapters.

1.2 What is Synchrotron Radiation? A qualitative description of its properties

The theory of synchrotron radiation based on the work of Ivanenko and Pomeranchuk (1944) and Schwinger (1946, 1949, 1954) has been described in detail during recent years, both in convenient summaries (e.g. Sokolov and Ternov, 1968) as well as in basic textbooks (Sommerfeld 1949, Jackson 1962).

For a quantitative description of the properties of synchrotron radiation a convenient starting point is Schwinger's formula for the total power radiated by a monoenergetic relativistic electron on a circular orbit (c.g.s units):

$$P = \iint I(\lambda, \psi)\, d\lambda d\psi = \frac{2}{3} \frac{e^2 c}{R^2} \left(\frac{E}{mc^2}\right)^4, \qquad (1)$$

where

$$I(\lambda, \psi) = \frac{27}{32\pi^3} \frac{e^2 c}{R^3} \left(\frac{\lambda_c}{\lambda}\right)^4 \gamma^8 [1 + (\gamma\psi)^2]^2 \cdot \left\{ K^2_{2/3}(\xi) + \frac{(\gamma\psi)^2}{1 + (\gamma\psi)^2} K^2_{1/3}(\xi) \right\}; \qquad (2)$$

λ_c is the "cut off" wavelength given by

$$\lambda_c = \frac{4\pi R}{3} \gamma^{-3}; \qquad \lambda_c(\text{Å}) = 5.59\, R(\text{meter}) \cdot \{E(\text{GeV})\}^{-3} \qquad (3)$$

$$= 18.6 \cdot B(\text{tesla})\, E^2\, (\text{GeV})\, \xi^{-1}$$

and

$$\xi = \frac{\lambda_c}{2\lambda}\,[1+(\gamma\psi)^2]^{3/2}$$

In the above expressions, $\gamma = E/mc^2$ where e, m and c have the usual meaning, λ is the wavelength of the emitted radiation, R the bending radius of the electron orbit, ψ the azimutal angle and $K_{1/2}(\xi)$, $K_{2/3}(\xi)$ are modified Bessel functions of the second kind (see for instance Watson (1945)). In Fig. 5 the characteristic directional pattern from a charged relativistic particle is sketched. The radiation is emitted into a very small angular cone around the particles instantaneous direction of flight. At the "cut-off" energy $\epsilon_c = hc/\lambda_c$ the angular width $<\psi>$ is $1/\gamma$; at lower energies $<\psi>$ varies roughly as $<\psi> \propto (\epsilon_c/\epsilon)^{1/3}$ for $\epsilon<\epsilon_c$.

The spectral power per unit photon energy $I(\epsilon,\psi)\, d\epsilon\, d\psi$ rather than per unit wavelength $I(\lambda,\psi)\, d\lambda\, d\psi$ (eq. 2) is more useful for many purposes:

$$I(G,\psi) = I(\lambda,\psi) - hc/\epsilon^2\, d\lambda = hc/\epsilon \tag{4}$$

For example, using eq. 4, the number of photons in an infinitely high slice of one mrad horizontal width for $\lambda > \lambda_c$ is given by

$$N \frac{\text{photons}}{\text{sec}\cdot\text{eV}\cdot\text{mA}\cdot\text{mrad}} = 4.5\times10^{12}\, j(\text{mA})\cdot(R(\text{m}))^{1/3}\cdot(\epsilon(\text{eV}))^{-2/3} \tag{5}$$

with j = particle current in the accelerator.

Synchrotron radiation from proton accelerators is negligible. For energies up to several hundred GeV the classical theory shows that due to the heavier mass of the proton only a negligible part of the emitted radiation power is in the range of the visible light spectrum or at shorter wavelength. Solely the abrupt change of the magnetic field occurring at the magnet edges can lead to emission of SR by a high energy proton beam (Coisson 1977) and indeed recently visible SR emitted by 400 GeV protons in the CERN super proton synchrotron (SPS) originating from the edges of the bending magnets has been observed (Bossart et al. 1979).

For applications in spectroscopy, x-ray scattering experiments and other applications, the following properties of SR from electrons (or positrons) are of prime importance:

1. Wide spectral range, intense continuum from the infrared to the x-ray region

The general shape for the radiation spectrum of an electron moving in a curved trajectory is shown in Fig. 6. The horizontal wavelength scale is defined by the quantity λ_c, known as the critical wavelength, and the vertical scale of intensity simply by the electron current and energy. In a practical device, the value of λ_c is given by the formula

$$\lambda_c = \frac{5.6\ R}{E^3} = \frac{18.6}{B\ E^2}\ |\text{Å}| \tag{6}$$

with E in GeV, R in meters, B in Tesla and 1 Å = 0.1 nm.

The shape of the spectrum shows that in order to obtain radiation extending from the x-ray region to the far infra-red, λ_c must be $\sim$ 1 Å or shorter; eq. (6) indicates that this can be achieved with a value of E of a few GeV and R a few metres.

As evident from eq. 5, the amount of radiation emitted from a storage ring is directly proportional to the number of stored electrons. The spectra of total emitted flux for several storage rings are depicted in Fig. 7. Here the number of photons per sec per an angular segment of 1 mrad horizontal width per 0.1% bandwidth is plotted versus a photon energy scale. The total flux is the important quantity for experiments which do not need resolution.

2. Excellent direction properties, high degree of collimation, spectral brilliance

The radiation emitted by a single electron emerges (for $\lambda = \lambda_c$) at a mean angle $\Theta \sim 1/\gamma$ where $\gamma = E/m_oc^2$, m_oc^2 being the electron rest mass energy (0.511 MeV). For E in the GeV region, this angle can be smaller than 0.1 mrad ($\sim 0.006^o$ or 20 sec of arc). The intensity of the radiation as a function of the elevation angle ψ against the orbital plane is shown for a specific storage ring as an example for three photon energies at the top of Fig. 8. Thus, the plane of the accelerator is filled with radiation, while the emission in the off-plane direction typically is confined to a wedge of only about one milliradian angular spread.

Together with the wide spectral range, the excellent directional properties can be exploited in order to obtain high spectral brilliance over a large spectral range. The spectral brilliance is the quantity to be taken into account for many experiments, e.g. in calculating the properties of an x-ray monochromator. The brilliance of the source depends on the extent of the radiating area as seen by an observer (see below); in this case, the source size and directional properties of the radiation enter. The average spectral brilliance as a function of wavelength for several synchrotron radiation sources is shown in Fig. 9. The output spectrum can further be enhanced in specific beam lines by the use of wigglers and undulators as described below.

3. Well defined polarisation

The radiation emitted by an electron in the plane of its orbit is 100% polarized with the electric vector parallel to the orbital plane. Above and below this plane, the radiation is elliptically polarized to a degree determined by the viewing angle.

The two factors in eq. (2) in square brackets are associated with the two components of polarization. The first describes the component with the electric field vector E parallel to the orbital plane, the second with E perpendicular to the plane. Using as the definition for the degree of polarization

$$P = (I_\parallel - I_\perp)/(I_\parallel + I_\perp) \qquad (7)$$

one obtains for P as a function of λ and ψ

$$P(\lambda, \psi) = \frac{K^2_{2/3}(\xi) - [(\gamma\psi)^2/(1+(\gamma\psi)^2)]\, K^2_{1/3}(\xi)}{K^2_{2/3}(\xi) + [(\gamma\psi)^2/(1+(\gamma\psi)^2)]\, K^2_{1/3}(\xi)} \qquad (8)$$

Thus, in the orbital plane ($\psi = 0$), the light is 100% linearly polarized. Taking the storage ring DORIS as an example, the degree of linear polarization parallel ($I_\parallel$) and perpendicular ($I_\perp$) to the orbital plane as a function of angular distance from the plane is shown in Fig. 8 for an energy of 3.5 GeV. The radiation off the plane of the orbit is not an uncorrelated superposition of parallel and perpendicular polarized components, but is elliptically polarized. It can be decomposed into left and right hand circularily polarized radiation as shown in the lower part of Fig. 8.

4. Fast time structure

Electrons circulate in compact groups (bunches) in storage rings in synchronism with an applied radio frequency field which replaces the energy lost by the emission of synchrotron radiation. The bunch length is

typically 50 psec to 1 nsec. Thus, as far as the time structure is concerned, the storage ring has outstanding properties; the radiation is emitted in short flashes of bunch length time and has a very stable intensity from bunch-to-bunch (see Fig. 10 for example). For spectroscopic experiments the repetition frequency is also an important parameter. It is determined by the repetition frequency of the filled bunches. Maximum separation between two pulses is obtained in the single bunch mode, i.e. only one bunch in the full ring orbit is filled. In this case the period of revolution determines the repetition frequency, which ranges from a few nsec to a few µsec. The experimentally determined pulse shape is shown for DORIS (Fischer and Rossmanith, 1972) and ACO (Lopez-Delgado et al. 1974) in Fig. 10.

The emission of SR in ordinary bending magnets is incoherent as Bénard and Rousseau (1974) have shown in their theoretical investigation of the statistical properties of SR as long as the wavelength is smaller than the length of the electron bunch. In particular the fields emitted at the same point by two successive pulses are completely independent.

5. Quantitatively known characteristics

The fact that the properties of SR can be quantitatively calculated with the help of a small number of well defined parameters is an important attribute of SR for the spectroscopist when planning and designing his experiments. Furthermore, this calculability is the basis for the now well established use of SR as a calibration standard in the UV, VUV and x-ray regions.

6. Clean environment ($p < 10^{-9}$ Torr), high stability of storage rings

SR is generated in an ultra high vacuum environment . This is an important attribute for many applications. Thus, e.g., experiments in surface physics who require windowless monochromators profit from this property. Clearly, the excellent stability of the source is an advantage.

In addition to these general comments concerning the properties of SR, let us summarize those parameters of primary consideration in describing the source properties in ordinary bending magnets, in wigglers and undulators. They are as follows:

Bending Magnets

a) The natural divergence of the emitted light which is equal to $1/\gamma$ at λ_c and which varies like $(\lambda/\lambda_c)^{0.43}$;

b) The divergence of the electron beam in the magnet (horizontal and vertical: σ_x' and σ_z');

c) The size of the source seen by the observer: the vertical size is the size of the electron beam itself (σ_z) whereas the horizontal size is determined by the horizontal size of the electron beam (σ_x) and by the segment (radius R, orbital angle Θ) accepted by the beam line optics, i.e. effective horizontal size = $\{\sigma_x{}^2+(R\Theta^2/2)^2\}^{1/2}$;

d) The total emitted flux per horizontal unit angle integrated in the vertical plane in a given bandpass (see Fig. 7 and Section 1.5);

e) The spectral brilliance as defined as the ratio of the total emitted flux divided by the product of the apparent beam size and the total divergence of the emitted beam (natural divergence + electron beam divergence) (see Fig. 9c and Section 1.5).

Thus far we have considered SR originating from the circular trajectories of electrons in bending magnets of storage rings. With the steadily increasing technological skills in accelerator design and the growing experience in operating such machines, very interesting devices for extending the capabilities of SR sources have become feasible. The principles of the most frequently discussed devices - wigglers and undulators - are sketched in Figs. 11 and 12.

Wigglers

The purpose of this device, which is located in a straight section of a ring, is to force the electron beam to execute a trajectory with a shorter local radius of curvature than in the dipole bending magnets by using a larger magnetic field. Such a wiggler increases the critical energy and shifts the overall spectrum to higher energy. Typically, $N \approx 5$-10 "wiggles" can be achieved by using 2N+1 poles with an increase of N in flux; one "wiggle" with three poles is shown in Fig. 11.

Undulators

Normal synchrotron radiation is emitted by charged particles submitted to a centripetal acceleration. However, it is well known that any kind of acceleration will give a light emission whose properties can be calculated via well-known relativistic electrodynamical equations. If relativistic electrons are subjected to particular configurations of periodic accelerations (e.g. using a periodic transverse magnetic field with N poles), quasi-coherent or coherent radiation can occur which has a very different spectral distribution than that of SR from a bending magnet. Two configurations which have been considered in detail are (i) a transverse sinusoidal magnetic field with period λ_o and maximum field amplitude B_o and (ii) a helical field in which the field amplitude remains constant but the direction of the field vector rotates around the axis of the undulator as a function of the distance y along the axis (see e.g. Winick and Knight, 1977; Spencer and Winick 1980, Farge 1980, and Winick et al. 1981).

The properties of the emitted light depends both on the geometry of the undulator and on the aperture of the electron beam travelling through this device. When an undulator is operated so as to obtain quasi-coherent radiation, the wavelengths of radiation seen at an angle Θ from the trajectory (nth harmonic) are

$$\lambda_n = \frac{1}{n}\,(1 + \lambda^2\,\Theta^2 + \alpha^2\,\gamma^2) \tag{9}$$

Eq. (9) is valid, if the number of poles $N > 2$ and $\alpha\gamma < 1$, with α being the maximum electron deflection angle.

The main characteristics of the radiation from an undulator are:

a) Strong angular dependence of λ (at $\Theta = 1/\gamma$, λ is double than for $\Theta = 0$). This makes it very important to have a small electron beam angular spread σ'. In fact, to select a band with a relative wavelength bandwidth ($\Delta = \Delta\lambda/\lambda$), the angular spread should be smaller than Δ^2/γ.

b) The form of the spectrum depends on the "deflection parameter" $K = \alpha\gamma = 0.01\ B_o\ \lambda_o$ (B_o in Tesla and λ_o in cm) which is independent of the electron energy. For $K << 1$ only one spectral harmonic is emitted ($\lambda = \lambda_o/2\ \gamma^2$); its wavelength is independent of B_o and the power emitted is proportional to B_o^2. For $K > 1$, many harmonics appear, their envelope being similar to a normal synchrotron radiation spectrum. The quantitative aspect of the spectrum for different values of the parameters $K = \alpha\gamma$ and $\sigma'\gamma$ is shown in Fig. 13.

At least three different modes of operation can be proposed:

(i) Curve a of Fig. 13: With a small deflection and a small angular spread, only one harmonic will be emitted through a small pinhole on the axis of the undulator. This harmonic will be almost independent of B and will have a low power compared to the case where $K \geq 1$.

(ii) Curve c of Fig. 13: With a large deflection and a small angular spread, high power is emitted through the same pinhole in many bands, which can be tuned with the magnetic field B. For a well collimated electron beam ($\sigma'\gamma << 1/\sqrt{N}$), the increase in spectral brilliance is proportional to N^2.

(iii) Curve d of Fig. 13: With a large deflection and no pinhole the spectrum is similar to the usual SR with a power multiplied by N ("multiple wigglers").

The usefulness of these devices and their properties are currently under active study at a number of places and recent reviews of this interesting topic have been given by Spencer and Winick (1980), Farge (1980) and Winick et al. (1981). The possibility of increasing the spectral brilliance by N^2 ($N \simeq 50$) is very exciting and will offer new opportunities. To illustrate the present state of these developments, we reproduce in Figs. 14 and 15 the emission of the ORSAY undulator and observations of undulator radiation at Tomsk.

Free Electron Laser

A future application of storage rings opened by the increasing capabilities offered by modern accelerator technology with the use of undulators is the operation of a free-electron laser (FEL). For a FEL in a storage ring, the basic idea is to obtain stimulated electromagnetic radiation directly from relativistic electrons. A schematic description of such a source appears in Fig. 16. The major components are a relativistic electron beam along the optical axis of an optical resonator, or optical cavity. A static spacially periodic transverse magnetic field along the axis forces electrons onto a path similar to that in an undulator. In this way, a gain for one particular frequency may be obtained. An optical resonator seems necessary in order to obtain high power.

Two experiments have been done at Stanford in 1975 and 1977 with an electron beam from a linear accelerator (Elias et al. 1976, Deacon et al. 1977, Pellegrini 1980) which have shown that it is possible to operate a free-electron laser. The construction of an FEL using the 0.7 GeV NSLS storage ring is underway at Brookhaven National Laboratory and is discussed for the storage ring BESSY in Berlin (Gaup and Madey, 1981).

Other Devices

At the end of this section we mention two other devices which might be interesting sources of SR, although until now they have not yet proven their technical feasibility as an advantagous "light source".

Intense relativistic electron rings used for the collective electron ring accelerator (e.g. Schumacher 1979) can emit a high-intensity continuum in the VUV spectral region . Although the ring dimensions are very much smaller (50 cm and smaller) than those of conventional storage rings the electron current in the rings can be made very high (several Kilo amperes). Schumacher (1981) has recently discussed such a device having a time averaged brightness higher in the VUV region than that of present day storage rings.

Particle channeling (e.g. Gemmel 1974) is another method which may be exploited as a radiation source. The principle is somewhat similar to that of an undulator. Relativistic charged particles channeled in a crystal undergo a periodic motion which should result in the emission of forward-directed electromagnetic radiation of relatively narrow linewidth. The radiation from these particles is predicted to be highly directional, linearly polarised and considerably more intense than ordinary bremsstrahlung on a per-unit-solid-angle per-unit-frequency interval basis, (e.g. Vorobiev et al. 1975; Kumakhov and Wedell 1977 and Pantell and Alguard 1979).
Alguard et al. (1979) have recently reported on the first observation of the emission of such channeling radiation using 56 MeV positrons and a silicon crystal. They found that the observed spectral peaks in the energy range of 30 to 50 KeV, correspond well to those predicted for the given parameters of their experiment.

1.3 Historical Remarks

Synchrotron Radiation and its use as a scientific tool has an interesting history. The prediction of the phenomenon, the search for this new kind of radiation, its discovery and the notion of its potential usefulness are indeed "and interesting case history" in modern science, as has been noted by G.C. Baldwin (1975) in his paper on the "Origin of Synchrotron Radiation"; (see also Kerst, 1975). In the following we highlight a few historical notes (Sokolov and Ternov, 1968, Haensel and Kunz, 1967, Madden, 1974, Kulikov 1976 and Lea 1978) being fully aware of the dangers associated with giving credit to "firsts" and with the limitations of relying principally on the published literature.

The phenomenon that an electron in a circular trajectory would radiate was predicted in a pre-quantum and a pre-relativistic language almost 100 years ago. At that time, it was well known from classical electrodynamics that accelerated charged particles radiate. J. Larmor (1897) gave an expression for the instantaneous total power radiated by a single, non-relativistic electron as

$$P = \frac{2}{3}\,\frac{e^2}{c^2}\left(\frac{dv}{dt}\right)^2 = \frac{2}{3}\,\frac{e^2}{m^2\,c^3}\left(\frac{dp}{dt}\right)^2 \qquad (10)$$

where e is the electric charge, c is the velocity of light, $\underline{v}$ and $\underline{p}$ are the velocity and momentum of the charged particle, respectively, and m is its rest mass. In 1898, A. Liénard (1898) published an extension of Labor's formula for the rate of radiation from the centripetal acceleration of an electron in a circular trajectory. G.A. Schott (1907, 1912) further developed the classical theory in connection with early models of the atom and in an attempt to describe the discrete nature of atomic spectra. As is well known, the Bohr model of the atom described the regularities in atomic spectra elegantly and the results of Schott's work were forgotten for a long time. No attempts were made to verify experimentally the conclusions of the classical theory and for more than 30 years radiation from an accelerated charge was mentioned only in textbooks (e.g. Abraham 1923, Abraham and Becker, 1933; and Heitler, 1936).

After this early work quite some time elapsed without noticeable progress until, in the 1940's, the subject of radiation from relativistic electrons received new attention in university and industrial laboratories. In the 1940's much effort was being devoted to the design of accelerators for the production of very high energy electrons and other charged particles, particularly in the US (e.g. Kerst 1941) and the USSR (e.g. Veksler 1944). It was recognized that the radiation losses incurred by electrons place severe limitations on the highest energies attainable, a principal inherent limitation which applies to the construction and operation of the "big circular machines" to the present day. On May 18th, 1944, a letter to the editor of The Physical Review entitled "On the maximal energy attainable in a betatron" by D. Iwanenko and I. Pommeranchuk (1944) was received. In a discussion of the operating principles of a betatron, the authors pointed out that radiation losses by electrons moving in a magnetic field imposed a limitation on the maximal attainable energy. They also stated that quantum effects do not play an important role, because the dimensions of the orbits are very large. A number of pertinent theoretical investigations of the problem followed.

We mention the papers of the group at Moscow University by Ivanenko, Sokolov and Ternov (Ivanenko et al., 1948; Sokolov et al., 1953; Sokolov and Ternov 1955; 1957 and 1964) and the work done quite independently by Schwinger in the US (Schwinger 1946 and 1949) who communicated his results to various persons interested in the design of accelerators prior to his extensive publications in 1949 (see e.g. the remarks in Schwinger's 1949 paper and the paper by McMillan, 1945). In the following years the number of papers devoted to a theoretical study of synchrotron radiation rose sharply (e.g. Olsen 1952 and Neumann 1963 and references therein). Without discussing the subsequent papers in detail we note that, within error bars, the classical and quantum mechanical approaches show close agreement, i.e. differences are negligible for the presently available accelerators.

The first experimental search for synchrotron radiation was only partially successful. In 1945, J.P. Blewett reported on results which appear to represent the first systematic investigation of radiation losses in an accelerator (Blewett, 1946). At the 100 MeV Betatron at the General Electric Laboratories at Schenectady, N.Y., Blewett observed a shrinking of the electron orbit at the highest energy of 100 MeV "in a manner consistent with the predictions of the theory". As stated in his abstract "the radiation itself has not yet been detected". The reason for this failure was the fact that the search for the expected radiation was made in the rf and microwave range from 50 to 1000 MHz with receivers capable of detecting less than 10 microwatts, while the energy distribution had its maximum at much higher frequencies in the near infrared and visible spectrum.

In May 1947, F.R. Elder, A.M. Gurewitsch, R.V. Langmuir and H.C. Pollock published a letter entitled "Radiation from Electrons in a Synchrotron" (Elder et al., 1947) in which they reported their visual observation of Synchrotron Radiation (SR) (see Fig. 17). We quote H.C. Pollock's account of the history of the discovery from his letter to Professor Ivanenko dated September 25, 1970 (We thank Prof. Ivanenko for kindly providing us with a copy).

"If the accelerator tube of the 100 MeV betatron at Schenectady had not been opaque, the visual observation would probably have been made three years earlier by W.F. Westendorp or J.P. Blewett soon after the publication of your letter to the Physical Review (Phys. Rev. 65, 343,1944). Unfortunately, they were not able to see through the silvered wall of the betatron donut.

In 1946 at Schenectady we began the construction of a synchrotron, both to test the synchrotron principle which McMillan had recently proposed and to see if electron injection by the betatron principle could lead to additional reduction in accelerator size. On October 24, 1946 my associate, Robert Langmuir, wrote to Ed McMillan that we had a synchrotron beam. But we did not "see" the beam until April 24, 1947 as I shall explain.

We had a magnet coil failure not long after our first successful synchrotron operation. Then followed various delays while we improved our guns, rf cavity resonator, and other equipment; and also, while there were experiments with a 50 MeV direct-current biased betatron in which our x-ray division was particularly interested.

By spring, the synchrotron was able to operate with much improved components and a much greater electron beam. On April 24, Langmuir and I were running the machine and as usual were trying to push the electron gun and its associated pulse transformer to the limit. Some intermittent sparking had occurred and we asked the technician to observe with a mirror around the protective concrete wall. He immediately signaled to turn off the synchrotron as "he saw an arc in the tube". The vacuum was still excellent, so Langmuir and I came to the end of the wall and observed. My notebook for that date reads as follows:

At first, we thought it might be due to Cerenkov radiation, but it soon became clear that we were seeing Ivanenko and Pomeranchuk radiation. The intensity remained high when we decelerated the electron beam from 70 MeV to 10 MeV without bringing the beam to the target or gun. We observed the bright spot with mirrors, looking tangent to the orbit at two or three points in the room. The intensity decreased as the peak energy was reduced. When the energy was of the order of 20 MeV, it was no longer visible. We showed the effect to Dr. Charlton, Dr. Kingdon and various others.
The beam appears stable and of small cross-section (perhaps 1 mm square).
(A copy of the April 24, 1947 page from the Synchrotron Notebook is attached.)".

According to Baldwins (1975) description of the first observation of SR it was Floyd Haber, the technician mentioned in Pollocks letter, who "ventured a very quick glimpse (with the aid of a mirror) around the corner of the radiation shield" (Baldwin 1975) and thus became the first to observe man made SR. Baldwins memory may have been at some fault in his letter and it seems that Gerald Knowlton was actually the first to observe the light. G. Knowlton submitted in 1976 to the American Institute of Physics a notarized affidavit in which he describes in strict legal way how, from inside the shielded area he observed the light and shouted out to Langmuir, how the machine was respondend to the latter's start up, fine tuning operation.

He noted how the "flickering spot of light" changed position with his own: " ---that affiant (then) moved his head along the orbit plane --- through a small angle ---, found that the bluish spot of light seen moved a like angle around the orbit -----." Haber, working at a bench in the area, left immediately prior to the observation and was gone during the critical twelve or fifteen minutes, Knowlton claims. The small mirror played no role, he indicates, but was later replaced with a large one by way of which many people subsequently saw the radiation (Hartmann, 1982).

In their letter to The Physical Review, Elder et al. (1947) already noted the polarization properties: "The light emitted from the beam is polarized with the electric vector parallel to the plane of the electron orbit. It disappears as the observer rotates a piece of Polaroid before the eye through ninety degrees."

In the following years Pollock and his group (Elder et al. 1948) studied the properties of synchrotron radiation more systematically by measuring with a spectrometer the intensity distribution from the 0.293 m General Electric Synchrotron in the wavelength region from 3500 to 7000 Å at several electron energies up to 80 MeV. High speed photography of the light permitted observation of the size and motion of the beam within the accelerator tube. We mention that the observation of SR is the most direct way to discover the electron. "SR is emitted immediately by the electron, moving in the electromagnetic field, which has no microstructure. The electron becomes "luminous" in the most literal sense". (Sokolov and Ternov, 1968).

These and further studies by Ado and Cherenkov (1956) and Korolev et al. (1953, 1960) carried out at th FIAN Synchrotron in the Lebedev Institute in Moscow for electron energies between 150 and 225 MeV gave satisfactory agreement between theory and experiment. At the 300 MeV Synchrotron at Cornell, Corson (1952, 1953) corroborated the shrinking of the electron orbit and proved the "E^4-law". Spectroscopic studies were extended into the VUV region 400 to 60 Å by Hartman and Tomboulian (1952, 1953), Tomboulian and Hartman (1954, 1956) and Tomboulian and Bedo (1958). Joos (1960) and Bedo et al. (1960) measured the polarization of SR. Early systematic studies of the properties of SR were also performed at the NBS 180 MeV synchrotron by Madden and Codling (1963, 1964a,b) and by Bathow et al. (1966) at the 6 GeV synchrotron in Hamburg. All these experiments confirmed the theoretical conclusions.

The 1956 paper by D.H. Tomboulian and P.L. Hartman (1956) marks the beginning of spectroscopy using SR as a source of VUV and soft x-ray radiation. In their paper they pointed out that "the electromagnetic radiation from centripetally accelerated high-energy electrons appears to be a useful by-product of such accelerators and is outstanding in its own rights". It took roughly another 15 years until the "by-product aspect" was no longer the major point of view and storage rings operated specifically for SR became available. Tomboulian and Hartman were the first to perform absorption measurements with a grazing incidence spectrograph in the far UV via a careful analysis of photographic plates. They recorded the spectra of metallic Be and Al. The Be K-edge and Al $L_{2,3}$ discontinuities occuring at 111 Å and 170 Å , respectively, were clearly seen in two orders. Their experiments also suggested the possibility to use SR in the VUV as a radiation standard. Recently, Hartman (1982) gave a vivacious personal recollection of these experiments.

The potential use of SR in x-ray physics was also discussed quite early. In his 1959 paper Paratt (1959) compared the prospective usefulness of SR from a 1 GeV and a 6 GeV synchrotron in the wavelength range of 0.1 to 20 Å with x-rays obtainable from a conventional x-ray tube. He also briefly discussed prospective experiments involving SR in the x-ray range including diffraction experiments for x-ray structure analysis and spectroscopic studies of absorption and fluorescence. Concluding his assessment of the use of SR in the x-ray range he noted that SR, provided the stability of the accelerators was good enough, "would be a boom in many aspects of x-ray physics".

We do not attempt to follow in detail the history from this point onward. It suffices to say that once the potential of SR became apparent, activities started at a number of places. Developments which occurred in the early 60's at the NBS in Washington (Codling and Madden, 1965), in Frascati, at the Institute for Nuclear Studies in Tokyo (Sagawa et al., 1966a, 1966b), at DESY, Hamburg (Haensel and Kunz, 1967), at the Physical Science Laboratory in Wisconsin, and at other facilities have been described in detail by Madden (1974). A description of the later developments may be found, for example, in articles by Lea (1978), Kunz (1979), Winick and Doniach (1980) and Rowe (1981). The list of topical reviews dealing with SR and its applications in the appendix of this handbook provides also an impressive documentation for the recent rapid proliferation of SR in many fields of science.

As a major advance, we mention the use of storage rings with greatly improved electron currents and stability in the beginning of the 70's. Around 1970, TANTALUS in Stoughton, Wisconsin, a 240 MeV storage ring, originally planned and operated in the 1960's as a test facility for advanced accelerator concepts, but later operated exclusively for SR work, came into full operation (Brown et al., 1966, Rowe and Mills, 1973, Gähwiller et al., 1973). After 1974 the ACO storage ring at Orsay was also exclusively used for SR research (Dagneaux et al., 1975 and Guyon et al., 1976). The first storage ring designed and built specifically as a light source is the 300 MeV INS-SOR storage ring in Tokyo (see Fig. 3) which went into operation in 1976 (Miyahara et al., 1976). At the same time, SURF II at the National Bureau of Standards, went into full operation as a 240 MeV dedicated storage ring (Ederer and Ebner, 1976) replacing the 180 MeV electron synchrotron there.

The use of larger storage rings ($E \geq 2$ GeV) so far still occurs mainly symbiotical with high energy physics (see Table 3). Of the large rings presently being used for experiments we mention especially (i) VEPP 2M and VEPP 3 at Novosibirsk (Anashin et al., 1976); (ii) SPEAR at Stanford, where since 1977 the Stanford Synchrotron Radiation Laboratory (SSRL) is in operation (Hodgson, Winick and Chu, 1976, Winick 1980), (iii) the 5 GeV storage ring DORIS at DESY in Hamburg (Koch et al., 1976; Behrend et al., 1978; Koch 1980; Beimgraben et al., 1981), and (iv) the 8 GeV storage ring CESR at Cornell providing radiation for a laboratory named Cornell High Energy Synchrotron Source (CHESS) (Battermann 1980 a, b).

At several of these laboratories improvement and expansion programs have greatly increased the usefulness of the storage rings as SR sources. For example, DORIS, which was used since 1974 right from its commissioning for SR experiments, is presently used as a part-time dedicated source (Behrend et al., 1978) by three institutions, Fraunhofergesellschaft, European Molecular Biology Laboratory, and Hamburger Synchrotronstrahlungslabor, which, aside from their own research projects, channel the efforts of a large user community in industrial and

applied physics (Heuberger, Betz and Pongratz, 1980), biophysics (Stuhrmann, 1978) and general physics and physical chemistry (Koch 1980; Beimgraben et al., 1981).

While the use of the above mentioned high energy storage rings occurs mainly symbiotically with high energy physics, we observe today the exclusive use of large storage rings by the community of SR users at several places (Table 3). A number of storage rings have now been specifically designed, built and operated or are in the planning stage as radiation sources. The 2 GeV storage ring at DARESBURY is the first large machine dedicated for SR. It started operation early in 1981 (Thompson 1980a). We further mention explicitly the Photon Factory Project at Tsukuba, Japan (Huke 1980, Kuroda 1980), the National Light Source project at Brookhaven (van Steenbergen 1980 a, b) and the detailed plans for the proposed European Synchrotron Radiation facility (Farge 1979; Farge and Duke, 1979; Thompson and Pool, 1979; Buras and Marr, 1979; Thompson, 1980b).

Some of the interesting current developments are the use of wigglers, such as studied in Moscow (Alferov et al. 1973, 1974) and pioneered at the Stanford Synchrotron Radiation Laboratory (Spencer and Winick, 1980; Winick et al. 1981), the imminent use of undulators, such as are being studied at Tomsk (Didenko et al. 1978) and ACO in Orsay (Farge 1980) and the construction of free electron lasers (Elias et al., 1976; Deacon et al., 1977; Pellegrini 1980) based on storage rings, such as the project at the National Synchrotron Light Source at Brookhaven National Laboratory.

The present level and range of interest and activity in the use of SR as a tool for research can be judged from a number of national and international reports which also contain a good deal of background information for an assessment of the historical developments (e.g. Morse 1976; Maier-Leibnitz 1977; Cardona 1977; Farge 1979).

As further sources for the recent historical developments concerning both the design and operation of machines and the many improvements in the general facilities and instrumentation, we refer to the proceedings of recent topical conferences (McGowan and Rowe, 1976; Willeumier and Farge, 1978; Ederer and West, 1980; Howells 1980; Mills and Battermann, 1982; see also Appendix I of this Handbook).

1.4 Modern Synchrotron Radiation Facilities

As a result of the research opportunities which became evident in the 1970's, the demand for synchrotron radiation sources significantly outran the supply. In response, a number of SR facilities have recently increased their capacity and a number of new dedicated storage rings have been built or are nearly completed. In the present section, we summarize the present status and briefly describe as examples a few of the modern synchrotron radiation facilities. The basic considerations and principles for storage ring design are treated in depth in Chapter 2 of this book.

Generally speaking, all the existing synchrotron radiation facilities at electron accelerators or storage rings fall in three general classes:
(i) facilities which use operating high-energy physics facilities symbiotically or "parasitically"; (ii) dedicated SR facilities which are converted facilities that were initially built for high-energy physics, and (iii) facilities designed, constructed and operated as dedicated SR facilities.

The present situation is described in Table 3, where relevant parameters for storage rings presently used as SR sources or under construction are compiled. In this list, the storage rings have been grouped according to their cut-off energy into four major categories. Machines in Groups I and II are excellent sources for VUV and soft x-ray spectroscopy. With their low particle energies and small diameters, restrictions imposed by radiation protection during operation are minimal and access is easy, which allows for small distances between the source points and instruments.

At larger machines (Group III), x-rays also become available for spectroscopic purposes and structural analysis; however, at the same time, radiation shielding becomes necessary and remotely controlled experiments are often required. Interest in the use of even larger machines (Group IV) for SR experiments has only been marginal with the exception of a few experiments proposed in nuclear physics (Chrien, Hofmann and Molinari, 1980). For the majority of experiments, the hard x-ray component of these sources, which is difficult to eliminate, is only an unwanted by-product. Furthermore, the current in these machines is generally very low and the distance from the source point to the laboratory site is large, because of the large radii. While interest in the short wavelengths (λ = 0.1 Å) attainable with these rings appears to be modest,

the use of undulators to generate intense radiation in the $\sim$ 1 Å range is an interesting potential development.

We do not attempt to describe individual SR-facilities in detail. Descriptions are disseminated by the facilities in their annual reports and in user booklets which describe sources, their characteristics, and instrumentation and access to these facilities.

As an example, let us look in some detail at the outline and design of the National Synchrotron Light Source (NSLS) built at Brookhaven which is similar to the SR center schematically shown in Fig. 4. The overall layout of the facility is given in Fig. 18. Electrons are accelerated in a linear accelerator to 100 MeV, injected in a multiturn mode into a booster synchrotron and accelerated to 700 MeV. The beam is then transferred either to the 0.7 GeV VUV-ring or to the 2.5 GeV x-ray storage ring. The combination of two high intensity storage rings and a multiplicity of monochromatized photon lines comprises the NSLS. The design, first proposed in its earlier stage by Chasman and Green (1977), has been described in detail by van Steenbergen and the NSLS staff (1980). With the incorporation of wigglers in the x-ray ring, the whole spectrum from hard x-rays to the VUV range is covered (see Table 4). In order to maintain precise control of the synchrotron radiation source locations and exit angles, an eleborate electron beam orbit detection and correction system is incorporated in both storage rings which is capable of maintaining source locations to within $\pm$ 0.1 mm. The VUV ring has eight ports which each deliver a fan of 75 mrad horizontal width and eights ports which each deliver 90 mrad. The x-ray ring will make use of 50 mrad ports, of which each will normally be split into two or more branches subtending typically $\sim$ 10 mrad per branch. Two high field wigglers are under developement, and eventually five high field wigglers will be incorporated in the x-ray storage ring. For the VUV ring, an undulator which is the basis of a free electron laser is under construction, and it is planned to incorporate a second undulator in the structure. The basic storage ring lattices have been optimized to achieve optimum source values at the various source locations in the storage ring structures. Furthermore, various beam operating modes are possible, so as to optimize brightness while sacrificing photon flux, or optimize photon flux with somewhat reduced brightness, etc.

As another example of an x-ray storage ring fully dedicated to SR research, the 2.5 GeV electron storage ring being constructed for the "Photon Factory" at the National Laboratory for High Energy Physics in Tsukuba is shown in Fig. 19 (Huke 1980). The storage ring has an elliptic shape with diameters of 68 m and 50 m. The basic structure of the ring consists of 28 bending magnets, 58 quadrupole magnets and many small magnets for orbit corrections. There are two 5 m long and eight 3.55 m long straight sections. The magnet structure will result in a flexible use of the storage ring as a SR source including the incorporation of wigglers and undulators. In the first stage of the project, a vertical wiggler magnet which produces fields of 6 T with a vertical deflection will be installed in one of the eight 3.55 m straight sections.

As another example of a modern VUV-machine, we briefly describe the BESSY project, a national synchrotron radiation facility presently under development in Berlin (Fig. 20). The choice of the principal design parameters has been described recently by Einfeld and Mülhaupt (1980). Beginning in 1982, this facility will be available for (i) applied research and industrial development in the field of x-ray lithography, (ii) metrology and (iii) basic and applied research in physics, chemistry, biology, medicine, etc. In order to meet the requirements of users working in these different fields, a lattice with a high flexibility has been chosen and six different electron beam optic modes have been worked out. Thus, e.g. with a "small emittance" mode, beam dimensions in the bending magnets of $\sigma_x = 0.08$ mm and $\sigma_y = 0.08$ mm are attainable. With a "small-bunch-length" mode, bunch lengths of 3ps can be reached for time-resolved experiments with, however, electron currents that are substantially lower than with ordinary bunch lengths. A "large emittance" mode allows a high electron current to be stored and provides a large acceptance for sweeping the beam, thus making this mode suitable for use in x-ray lithography.

These few examples give ample evidence of the large efforts being made to improve the availability and properties of SR sources. Further projects, such as the development of a European Synchrotron Radiation Center built around a 5 GeV electron storage ring and possibly a VUV ring have actively been studied (Farge 1979; Thompson 1980; Thompson and Pool, 1979). With the rapid development rate at present, it is difficult to assess future developments in this field. Certainly, the large capacity for production of SR

(see Table 3) will be used effectively. In parallel, new designs of lattices and sources optimized for specific purposes will be developed. Thus, e.g., there might be a demand for a simple, inexpensive and easy to operate small VUV storage ring which, though lacking the virtue of high flexibility, can be used very effectively for solid state and atomic and molecular spectroscopy or for x-ray lithography. The storage ring presently under construction at the Institute for Molecular Science Okazaki is a good example for this development (Watanabe, et al. 1980). The possible exploitation of SR in industrial laboratories for x-ray lithography may even trigger the development of "table top" machines, e.g. small simplified storage rings making use of superconducting magnets. Such a project is presently under active study at the Technical University of Munich (Jahnke et al. 1981).

1.5 Comparison of the Properties of Synchrotron Radiation to other Sources

Questions raised time and again by the conscientious experimentalist include: How does SR compare with other sources? Can an experiment be carried out profitably with SR? Is there an alternative (conventional) source which is either more convenient and inexpensive to use or even superior in quality compared to SR? Clearly, this kind of question cannot be answered in general. For each experiment or class of experiments, a detailed analysis of specific requirements is needed, i.e. spectral range, limiting source characteristics, compatibility requirements, etc. For example, it is obvious that the "power" or "intensity" of a source cannot be discussed considering the source alone; rather, the acceptance and transmittance properties of the measuring apparatus must be included.

The purpose of the present section is to provide a semiquantitative comparison and to give a few key references where such comparisons, each with different aspects, have been made in the past (e.g. Kunz 1974; Koch 1977; Jortner and Leach, 1980; Munro and Saberski, 1980; Bonse 1980, Koch 1981; and references in Tables 5 and 6). We caution the reader that more detailed statements and general comparisons can be easily misinterpreted (and have in the past) and can even be open to objections. Ultimately, the comparison depends on the success of experiments, and the following chapters in this handbook dealing with research applications of SR give evidence for the utility of SR.

For a quantitative definition of the source characteristics we refer to Fig. 21. Generally, the spectral flux of a source (number of photons per sec per 0.1% $\Delta\varepsilon/\varepsilon$ bandwidth) as well as its directional emission characteristics are of importance. It is convenient to define the spectral source brilliance (sometimes also called brightness):

<u>brilliance</u>

$$n\ (x, z, \theta, \psi, \varepsilon, t)\ [\text{phot s}^{-1}\ \text{mm}^{-2}\ \text{mrad}^{-2}\ \text{per } 0.1\%\ \Delta\varepsilon/\varepsilon] \qquad (10)$$

where n is the number of photons with energy ε emitted at a time t from the source point (x, z) along the direction (θ,ψ) per time interval, unit source area, unit solid angle and 0.1% bandwidth.

The intensity N is given by integrating over the source area:

<u>intensity</u>

$$N(\theta, \psi, \varepsilon, t) = \int_{\text{source}} n\ dx\ dz\ \ [\text{phot s}^{-1}\ \text{mrad}^{-2}\ \text{per } 0.1\%\ \Delta\varepsilon/\varepsilon] \qquad (11)$$

The spectral flux ϕ_s is obtained by integrating over the solid angle Ω:

<u>spectral flux</u>

$$\phi_s\ (\varepsilon, t) = \int_{\Omega} N d\theta\ d\psi\ \ [\text{phot s}^{-1}\ \text{per } 0.1\%\ \Delta\varepsilon/\varepsilon] \qquad (12)$$

The total flux is given by:

<u>total flux</u>

$$\phi_T\ (t) = \int_0^{\infty} \frac{1}{\varepsilon}\ \phi_s\ d\varepsilon\ \ [\text{phot s}^{-1}] \qquad (13)$$

In a storage ring, the size and angular spread of the electron beam varies at different points of the orbit. σ_x and σ_z [mm] denote the standard deviation of horizontal and vertical beam dimensions, respectively (full width at half maximum is 2.35σ). Thus, the source area F is given by $F \equiv \sigma_x\ \sigma_y\ (2.35)^2$ [mm^2]. Similarly, the standard deviation of horizontal and vertical angular beam divergence are denoted by σ_x' and σ_y' [mrad], respectively, and $\Omega = \sigma_x' \cdot \sigma_y'\ (2.35)^2$ [mrad^2] is the solid angle of emission.

The position of an electron and its angle, both measured relative to the equilibrium orbit, are correlated. This correlation is depicted in phase-space plots (electron emittance ellipse) of angle and position in the horizontal (orbital) plane and vertical plane (see Fig. 22). Electron emittances ε_x, ε_y are important beam characteristics which are defined as follows:

<u>horizontal emittance</u>

$$\varepsilon_x = \sigma_x\ \ \sigma_x'\ \ [\text{mm} \cdot \text{mrad}] \qquad (14)$$

<u>vertical emittance</u>

$$\varepsilon_z = \sigma_z\ \ \sigma_z'\ \ [\text{mm} \cdot \text{mrad}] \qquad (15)$$

The area of these ellipses is invariant along the electron path, i.e. ε_x and ε_y are conserved, while the shape and orientation of these phase space ellipses change from point to point on the orbit. This is discussed in more detail by Watson, Perlman and Krinsky in Chapter 2 of this Handbook. When comparing sources these definitions have to be kept in mind, because different experiments usually require different parameters to be maximized. Thus, e.g., protein crystallography using x-ray diffraction requires high spectral source brightness (large flux on small sample areas with minimum angular divergence), while in other experiments maximum spectral flux is required.

Armed with the above caveats and definitions, we present in Tables 5 and 6, and Figs. 23 and 24 a number of alternative sources grouped according to spectral range. Also indicated are the spectral ranges in which different types of monochromators can be used for selecting particular energies for an experiment.

There are only a few experiments, such as energy dispersive x-ray scattering or x-ray microscopy which can make use of the continuum without monochromatization. The demanding and sometimes tedius tasks of designing, fabricating and operating these monochromators, which are presently far from being commercially available laboratory equipment, is still one of the major difficulties in optimizing the use of SR. Basic principles and practical examples for VUV and x-ray monochromators are described in detail by Johnson and Matsushita and Hashizume in Chapters, 3 and 4 of this Handbook. However, similar problems exist with all alternative continuum light sources and even with many line sources when unwanted satellite lines have to be suppressed (e.g. He II source and conventional x-ray line sources for photoelectron spectroscopy).

Infra-Red

In the infra-red region, the radiation per unit bandwidth decreases less rapidly with increasing wavelength than that of the continuum of radiation emitted from a black-body radiator. For wavelengths $\lambda = 100 - 200\ \mu m$, synchrotron radiation sources can in fact provide more radiation flux than a black body source (Stevenson et al., 1973). Against this higher flux must be set the much greater physical convenience of the black body source. Nevertheless, the prospect of constructing an intense tunable infra-red source, such as a free electron laser, makes the use of synchrotron radiation in this wavelength region a most attractive proposition.

Visible Light and Vacuum Ultraviolet

For wavelengths below about 2000 Å, the SR source is superior to conventional sources for most experiments, because of its high intensity, polarisation and tunability. This is schematically indicated in Fig. 24, where the dependence of the spectral distribution of SR on the energy of the particle is sketched and compared to the most commonly used rare gas continua (Tanaka et al., 1958; Samson 1962). The rare gas continua extend from the visible to beyond 600 Å with a maximum flux of about 10^9 photons/sec Å (5×10^{10} photons/sec eV) at the helium maximum of about 800 Å. Similar values hold for the other rare gases (see Table 6). Only the 21.2 eV HeI resonance line as emitted from a capillary discharge, has an intensity comparable to synchrotron radiation. Both the emission and absorption lines superimposed on the continua of rare-gas lamps are severe limitations.

When one adds to this the fact that tunablility and polarisation are entirely absent for the discharge lamp, there is no doubt that SR is superior for practically all applications.

Comparison must also be made with vacuum ultraviolet lasers which operate at the present time down to about 1400 Å (Table 7). Here the intensities in photons/second may easily exceed those available from a SR source in the narrow bandwidth and extremely short range of tunability associated with laser operation. The difference in intensity of the laser and the SR may be put to good effect by using the narrow bandwidth and power of the laser to generate a high density of population of a specific molecular excited state which can then be immediately interrogated with relatively low power SR over a broad range of tunability. Temporal coherence available in a laser source is not in general provided by SR except to a limited extent from an undulator magnet. Also, the pulse length of present-day vacuum ultraviolet lasers is shorter by several orders of magnitude compared with time resolutions in the ten picosecond region which can be obtained using SR.

A critical discussion of the properties of VUV sources for time-resolved spectroscopy has been given by Munro and Sabersky (1980) and Rehn (1980). The main points of a comparison of pulsed light sources are compiled in Table 8 (see also Fig. 10).

Studies of the intensity distribution within a single individual bunch have recently been reported by Rehn (1980) for the storage ring SPEAR, which has similar parameters as DORIS (Fig. 10), as far as the time structure is concerned (bunch length 100 to 240 psec, single bunch repetition frequency 780 nsec). Using a streak camera, various modes of electron bunch-shape oscillations have been observed. These were found to be sensitive to beam current, electron energy and accelerator cavity voltage. With higher demands for better time resolution in time resolved spectroscopy these phenomena deserve more attention.

Schwentner et al. (1979) have described the present status of time-resolved experiments at storage rings and have discussed some aspects of how to reduce the pulse length of SR pulses emitted from storage rings and thus how to improve time resolution.

It appears likely that in the near future free electron lasers will be available in the wavelength range from 1200 $\AA$ to the far infrared, with powers ranging from a few watts to $\sim$ 1 kW according to the wavelength. The availability of coherent radiation of high intensity extending into the vacuum ultraviolet would provide a unique capability which is not available with present sources.

While the characteristics of the traditional rare gas continua and discharge lamps and resonance line sources are well documented and their properties have been largely explored (Samson 1962), there is still room for significant development of sources of VUV and x-ray radiation generated in hot plasmas produced either by a focused laser or a focused electron beam (see e.g. Ehler and Weissler, 1966; Carroll et al., 1978; Baker and Burgess, 1978; Mallozzi et al., 1974; Nagel 1980; Yamaguchi 1979; Mahajan 1979, McCorkle and Vollmer, 1977).

Recently, plasma sources have been developed mainly for soft x-ray lithography and microscopy and for work directed towards laser fusion. A very intense pulse of laser light striking a target (e.g. Yb, Sm, Cu, Al) produces a hot plasma near the vaporized surface. The plasma, in turn, emits a burst of soft x-rays. The low repetition rate of these devices, their low stability and unproven reliability appear to be drawbacks. However, improvements appear feasible within the near future in several instances.

X-Ray

In the wavelength region below 10 $\AA$, SR has to be compared with x-ray tubes. In the conventional x-ray tube, the radiation is produced in two distinct ways - the

rapid deceleration of electrons as they strike the anode and the excitation of electronic core levels in the atoms of the anode. These core levels are excited by transfer of energy from the incident electrons and subsequently de-excited by the emission of x-rays. Both these processes are very inefficient as far as x-ray production is concerned, and more than 99 per cent of the electron energy is converted into heat at the anode. The dissipation of this heat constitutes a severe practical limitation on the production of x-radiation by x-ray tubes (see e.g. Yoshimatsu and Kozaki, 1977).

In an electron storage ring, the radiation is produced entirely by accelerating electrons, but in this case the acceleration is a continuous process generated by the magnetic field of the guiding dipole magnets which cause the electrons to follow a curved trajectory in the storage ring. This process is far more efficient - almost all the energy supplied to the electrons is converted into radiation, though not all of this is in the x-ray region.

An x-ray tube is charcterized by an isotropic brilliance (number of photons/ apparent area x unit solid angle x unit energy interval x unit time). The characteristic lines emitted by an x-ray tube have about 10^3 times more intensity than the bremsstrahlung background. Its emission in time is continuous. In all these respects it differs markedly with respect to synchrotron radiation (see Fig. 25). In its narrow angular range, the brilliance of SR is several orders of magnitude greater than that of x-ray tubes.

Proceeding now to a more detailed comparison in terms of experimental features of the two sources, the following comments can be made:

Spectral brilliance; The limitation of heat dissipation for x-ray tubes coupled with the mechanical properties of materials means that there is a limit to the size of the electron focus. This limit, combined with the approximately isotropic distribution of the emitted photons, means that for all experimental situations which require the radiation to reach a small sample, the x-ray tube is greatly inferior to a synchrotron source, which has a much smaller source size and produces a well collimated beam of radiation. To give a realistic comparison between these sources, we present in Table 9 a comparison between a 2.4 kW rotating anode tube and a 100 kW rotating anode tube with a present-day synchrotron source and an estimation for the proposed

European Synchrotron Radiation Facility (ESRF). The comparison is made in terms of different experimental configurations and in each case an improvement factor is given relative to unity for the x-ray tube. The advantage of the synchrotron source can be seen clearly.

Other important characteristics;

compared to an x-ray tube, SR has the following important features:

(i) Full range of wavelength tunability over the entire x-ray region up to ∿ 200 keV.

(ii) Pulsed time structure free of electronic noise.

(iii) High degree of polarisation compared with the x-ray tube which is an unpolarised source.

For a further detailed discussion and comparison we refer to the recent paper by Bonse (1980).

γ-rays

As mentioned above, interest in SR from very large storage rings, such as PETRA or PEP has thus far been minimal. Thus research possibilities and comparisons with alternative sources have not yet been explored in any detail. As previously mentioned, undulators on these machines offer the intriguing potential of being extremely intense sources in the conventional x-ray range. Critical energies are 43.8 keV for PEP running at 15 GeV and 75 keV for PETRA running at 19 GeV, and thus the spectral distributions extend well into the hard x-ray region. The spectrum of synchrotron radiation from the proposed large European electron - positron storage ring facility LEP would extend into the γ-ray region. Recently, Chrien, Hofmann and Molinari (1980) have described the research possibilities of this latter machine in nuclear physics. LEP would have electron beam energies ranging up to 86 GeV. Radiation from the bending magnets would have a critical energy of 0.4 MeV. The use of wiggler magnets would easily extend the critical energy up to 10 to 20 MeV. Many potential users are probably still unaware of these developments, including the possibility to use SR as a source of low energy neutrons (Chrien, 1980).

A qualitative comparison of unmonochromatized SR from PETRA with γ-ray sources based on data given by Yelon (1976) appears in Fig. 26. From this comparison the SR flux seems to be superior to the flux produced by nuclear sources.

However, as with the other spectral ranges, more detailed comparisons must be carried out for specific experiments. Such a comparison of gamma ray source properties for studying electron momentum densities via the Compton effect has been presented by Cooper (1979). Considering the nature and intensity of currently available sources (x-ray, γ-ray, SR), he came to the conclusion that for Compton scattering, radioactive γ-ray sources with energies exceeding 100 KeV are optimum. Again, this situation is very likely to change with the recent improvements of SR sources, and trial measurements at DARESBURY (Holt et al. 1978) have already established the advantage of using SR for this type of experiments.

1.6 Research with Synchrotron Radiation

In the past ten years, the impact of synchrotron radiation on research in physics, chemistry, biology and in applied sciences has become pervasive, both in the VUV and x-ray regions. We have briefly touched upon the new possibilities and research applications offered by modern SR sources, but up to this point have mainly discussed the characteristics of SR and its sources. The latter is treated in depth in Chapter 2 of this handbook, while the principles of monochromator design and beamline optics are described in Chapters 3 and 4. These chapters together with the description of the operating principles and characteristics of photon and particle detectors (Chapters 5 and 6) provide basic background information needed by experimentalists to design and optimize their experiments for optimal and efficient use of SR.

A general introduction into the field of SR and its applications would, however, be incomplete without mentioning the principles of its many research applications. Here we can only mention a few selected areas where SR has proved to be a powerful and indispensible tool. In fact, descriptions of the numerous and diverse research applications of SR, descriptions of their principles, and illustrations by selected examples form the central part of this handbook and planned forthcoming volumes. Thus, the following is a rather general and brief synopsis of SR research.

The theoretical framework within which most of the work concerned with the electronic structure of matter is treated has been developed in the last two decades to a high degree of sophistication (see e.g. the review by Kotani and Toyozawa, 1979). The principles are discussed in Chapters 7, 8, 9 and 10 and illustrated by selected examples. Although important advances in the theoretical description of inner-level spectroscopies (e.g. Chapter 7) and the band structure of solids (Chapter 8) have been made, there are still severe limits to the predictive capabilities of the theoretical models. This is particularly due to the omnipresence of complications due to many-electron effects (Chapter 9). Fortunately, a close and intense collaboration between theory and experiment occurs in these areas which is advancing our understanding of new experimental observations obtained from SR experiments.

Many kinds of different experiments using SR have been made on all classes of substances and systems (Figs. 27 and 28), and the following is a brief summary of this research.

In atomic and molecular physics SR offers the unique possibility to tune the excitation energy in optical or photoelectron emission experiments so as to optimally probe binding energies ranging from those of loosely bound valence electrons up to energies corresponding to the most tightly bound core levels. The studies include both ground state systems as well as higher excited states. Fundamental quantities, such as binding energies, their shifts in molecular environments, potential curves and $h\nu$-dependent cross-sections may be determined over extended energy ranges. In addition to the static properties determining the energetic structure of the systems, dynamical processes, such as relaxation and energy transfer processes, are receiving increasing attention. All of these studies (Chapter 7) which originate from the interaction between light and the electronic charge, are the basis for further developments and refinements of theoretical models.

This general understanding is basic to a large number of more obvious important phenomena, such as (i) photon-induced chemical reactions in plasmas and in various regions of the atmosphere, (ii) the performance of molecules and clusters on surfaces in catalyzing chemical reactions, (iii) energy transfer processes between molecules or molecular assemblies as an important step in biological processes and (iv) the development and improvement of spectroscopic techniques used in applied research (e.g. for the development of VUV lasers).

The electronic structure of solids and surfaces is subject of widespread interest and an area of much active research with SR. Early applications of SR in this field were in optical absorption and reflection spectroscopy (e.g. Lynch 1979). While a certain foundation in the understanding of optical properties of solids in this hitherto largely unexplored frequency range was established by these studies, much more refined and extended investigations have become possible by the study of secondary and second order processes. In particular, photoelectron emission and luminescence spectroscopy when combined in their many forms with a tunable SR source have proven to be versatile and powerful probes of the electronic structure of solids and surfaces. Photoelectron spectroscopy (Chapter 10) encompasses a wide range of topics, such as atomic and molecular cross-section effects, accurate determination of binding energies and material-induced binding energy shifts, valence band structure (i.e. one-electron energy band versus momentum $E(\underline{k})$ dispersions) for solids and for two dimensional surfaces, intrinsic surface states, adsorbate systems, surface reactions, etc. Information on these topics is of central interest because they are fundamental for our understanding of the chemical and physical properties of solids and surfaces. Moreover, the experimental results provide not only crucial tests for any theoretical model, but have also many interesting and important applications. For example, the topic of adsorbates and surface reactions covers basic mechanisms of catalysis, corrosion and oxidation.

Synchrotron radiation has given new incentives to a large variety of classical methods in structural research. This is especially true for the application of Extended X-Ray Absorption Fine Structure (EXAFS), that is the absorption of x-ray radiation (rather than diffraction) as a powerful tool to determine the local arrangement of atoms. The principles and application of this technique are described in Chapter 11.

In Chapter 12, a summary is given of the elementary theory of diffraction of electromagnetic radiation in the x-ray region. X-ray diffraction is a well established and very important tool for determining the geometric structure of matter. In the same chapter, various experimental methods are described and new possibilities offered by SR for elastic scattering studies reviewed. For example, the use of SR for the classical methods offers the advantages of obtaining increased reliability or higher resolution in space or time. Furthermore, a number of new ideas can be realized effectively for the first time with SR. Among these we mention x-ray interferometry, real time topography and real time diffraction which can be used for kinetic studies of phase transitions, polymerization or muscle contraction in biological fibres.

Investigations with SR are not confined to research in basic sciences. Many of the experimental methods can serve as unique tools in applied research. The electronic structure of solids plays a fundamental role for an understanding of their physical properties, e.g. optical, magnetic, electronic, chemical, etc. Today, the optical properties of a large number of elements are being studied over extended hitherto unexplored spectral ranges, largely with the use of SR (e.g. Weaver et al., 1981). These and similar data for semiconductors and new materials (including organic compounds) may serve as a yardstick for builders and users of optical systems currently being explored and their potential applications in the fields of astronomy, microlithography and microscopy in biology and medicine, which are under active study and development.

x-ray lithography is yet another area of applied research which benefits from SR. It is perhaps the most obvious example of how work with SR is becoming increasingly important in technology. The final chapter (Chapter 14) of this handbook gives an introduction to this field and provides a large amount of practical information applicable to the design and evaluation of x-ray lithography systems and processes.

In summary, this Handbook on Synchrotron Radiation provides a concise and up-to-date picture of the present situation and gives easy access to a broad range of information concerning SR methods and its many applications in basic and applied science[1]. While the principles and basic methods are stressed in the present volume, it is intended to provide in depth summaries of the diverse results from VUV applications and x-ray applications of SR in Volumes II and III, respectively.

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1) The increasing range of applications of SR in various fields of science is also documented in the appendix of this handbook, where several books and major review articles dealing with SR and its properties - each with a different emphasis - have been listed in chronological order.

1.7 Future Prospects

Today SR is used in more than 20 laboratories throughout the world. A number of institutes have just begun with their programs for using SR, or are in the process of making their facilities available to a large community of users. One can safely predict that there will be a steadily increasing output of interesting and new results in many scientific disciplines from these laboratories. This is in particular true for many of the x-ray synchrotron radiation applications which have just begun. Unfortunately, space considerations preclude mention of several important but developing uses of SR in this introduction. Although it would be tempting to comment on these, we refrain from doing so and refer to the ensuing chapters.

The development and use of superconducting wigglers, as well as the improvement of simple and inexpensive permanent magnet wigglers will greatly increase useful intensities by a factor of ten to a hundred. In certain spectral ranges even these intensities will be greatly surpassed by SR from undulators. These future improvements of SR sources will be, by today's standards, spectacular. The greatly improved sources will undoubtedly be a driving force for new instrumentation and new techniques and will permit entire new classes of applications and lead to new breakthroughs.

In summary, during the last two decades SR has matured from being an unwanted byproduct of high energy electron accelerators to being a widely used source of radiation in the VUV and x-ray range which is in increasing demand. It is apparent that SR has an assured future for some time to come as a tool for research in basic and applied science.

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In preparing this introduction we have heavily relied upon the work of many of our colleagues and friends who over the past years have enjoyed with us the extraordinary developments of research with synchrotron radiation. We have tried to acknowledge their work and achievements throughout this introduction and again wish to thank them here for their advice, help and criticism. It is impossible to express our thanks individually to all of them. However, we wish to thank Yves Farge who has made significant contributions to the outline of the whole handbook project and to this introduction specifically.

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Table 1: Research fields in which Synchrotron Radiation is used and corresponding spectroscopic techniques (after Farge and Duke, 1979).

	Atomic physics	Molecul. physics	Photo-chemistry	Electronic properties of solids	Electronic properties of surface and adsorb.	Order/disorder in solids and liquids phase trans.	Local order in condensed phases, clusters	Defects in solids	Nuclear physics	Chemistry	Molekular biology	Cellular biology	Geology
Absorption/Reflection spectroscopy	x	x	x	x	x				x		x		x
Emission spectroscopy (energy and time resolved)	x	x	x	x	x				x		x		x
EXAFS and near edge X-ray structures			x	x	x	x	x	x		x	x	[illegible]	x
Photoelectron spectroscopy (UPS - XPS)	x	x	x	x	x					x	x		x
Photoion spectroscopy	x	x	x		x					x			x
Photoconductivity			x	x	x					x			
X-ray fluorescence analysis	x	x	x	x	x		x	x		x	x	x	x
Mössbauer spectroscopy	x	x				x	x	x	x		x		x
Inelastic scattery of photons	x	x		x						x			
X-ray diffraction scattering			x	x	x	x				x	x		x
X-ray diffuse scattering			x		x	x	x	x		x	x		x
Small angle X-ray scattering			x			x		x		x	x		x
Topography								x					x
X-ray interferometry	x	x		x	x						x		
X-ray radiography								x				x	x
X-ray microscopy								x			x	x	x

Further research areas include: radiometry, lithography and submicron device fabrication.

Table 2: Basic Synchrotron Radiation Relationships

ELECTRON ENERGY: E (GeV)
RADIUS OF CURVATURE: R (meters)
ELECTRON CURRENT: I (Amperes)
MAGNETIC FIELD: B (Gauss)

Total power radiated by a relativistic electron

$$P = \int I(\lambda,\psi)\,d\lambda\, d\psi = \frac{2}{3}\;\frac{e^2 c}{R^2}\;\frac{E^4}{(m_o c^2)^4}$$

Energy loss per turn, per electron

$$\delta E\ (\mathrm{keV}) = 88.5\ \frac{E^4\,(\mathrm{GeV})}{R\ (\mathrm{m})}$$

Total power radiated:

$$P_{tot}\ (\mathrm{kW}) = 2.66 \cdot E^3\ (\mathrm{GeV}) \cdot B\ (\mathrm{K\Gamma}) \cdot I\ (\mathrm{A})$$

Critical wavelength:

$$\lambda_c\ (\text{Å}) = 5.59\ \frac{R\ (\mathrm{m})}{E^3\,(\mathrm{GeV})} = \frac{186.4}{B\ (\mathrm{K\Gamma}) \cdot E^2\,(\mathrm{GeV})}$$

Characteristic energy

$$\varepsilon_c\ (\mathrm{eV}) = 2218 \cdot \frac{E^3\,(\mathrm{GeV})}{R\,(\mathrm{m})} = 2.96 \cdot 10^{-7}\ \frac{\gamma^3}{R\,(\mathrm{m})}$$

Emission angle: $\approx \frac{1}{\gamma} = \frac{mc^2}{E}$

$$\text{with } \gamma = \frac{E}{m_o c^2} = 1957 \cdot E\ (\mathrm{GeV})$$

Energy of a photon: $\varepsilon\,(\mathrm{eV}) = \frac{12.40}{\lambda\,(\text{Å})}$

References:

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Schwinger, J., Phys.Rev. 70, 798 (1946); 75, 1912 (1949)
Green, G.K., Spectra and Optics of Synchrotron Radiation BNL Report 50522 (1976)

Table 3: Storage rings used as synchrotron radiation sources; most of them are dedicated as light sources. E, particle energy; R, magnetic radius; I, maximum current; ε_c, characteristic photon energy; SR, synchrotron radiation. The numbers on the proposed storage rings usually are subject to changes; in the wiggler sections ε_c will be much larger than the values quoted for bending magnets. (Status as of summer 1981)

Name	Location	E (GeV)	R (m)	I (mA)	ε_c (eV)	Remarks
Group I $\varepsilon_c \lesssim 200\mathrm{eV}$ ($\lambda_c \gtrsim 62$Å)						
E 100	Karkov	.100	.5	25	40	
TANTALUS I	Stoughton, Wisconsin	.24	.64	200	48	dedicated
SURF II	Washington	.24	.83	30	37	dedicated
INS - SOR II	Tokyo	.4	1.1	250	130	dedicated
PLAMIA I	Kurtchatov, Moscow	~.45	1.0	100	~200	dedicated, under construction
Group II $\varepsilon_c \approx 200 - 2000\mathrm{eV}$ ($\lambda_c \approx 62 - 6$Å)						
ACO	Orsay	.55	1.11	100	333	dedicated, undulators
MAX	Lund	.56	1.2	200	300	dedicated, under construction
UVSOR	Okazaki	.6	2.2	500	216	dedicated, under construction
VUV	Tsukuba	.66	2.0	100		dedicated, under construction
VEPP-2M	Novosibirsk	.67	1.22	100	540	partly dedicated
NSLS VUV	Brookhaven	.70	1.9	500	400	dedicated, wiggler under construction
CHI-I	Hefei, China	.6	2.7	300	420	dedicated, proposed
ERNA	Munich	.43	,2865	500	620	dedicated, approved supraconducting magnet
SILVA	California	.8	~1.6	300	630	proposed
BESSY	Berlin	.8	1.83	500	630	dedicated
SUPER ACO	Orsay	.8	1.8	500	620	proposed and approved
IND-I	India	~.9	~2.0	-	700	proposed
ALADDIN	Stoughton, Wisconsin	1.0	2.8	500	1.070	dedicated, wigglers
ADONE	Frascati	1.5	5.0	60	1.500	partly dedicated, wiggler
Group III $\varepsilon_c \approx 2 - 50\mathrm{KeV}$ ($\lambda_c \approx 6 - 0.25$Å)						
DCI	Orsay	1.8	3.82	250	3.390	partly dedicated
TPP	Moscow	2.0	5	1000	3.500	proposed
SRS	Daresbury	2.0	5.55	500	3.200	dedicated, wigglers
VEPP 3	Novosibirsk	2.2	6.15	100	4.300	partly dedicated, wiggler
NSLS X-RAY	Brookhaven	2.5	8.17	500	4.200	dedicated, wiggler
PHOTON FACTORY	Tsukuba	2.5	8.33	500	4.160	dedicated, wiggler
PLAMIA II	Kurtchatov, Moscow	2.5		300	7.000	dedicated, proposed, wigglers, undulators
SPEAR	Stanford	4	12.7	100	11.100	partly dedicated
ESRF		5	22.36	500	12.400	dedicated, proposed, wigglers, undulators
DORIS II	Hamburg	5.7	12.12	100	31.950	partly dedicated
CESR	Ithaca	8	32.5	100	35.000	part time SR use
VEPP 4	Novosibirsk	7.0	16.5	10	46.100	partly dedicated, with wiggler
Group IV $\varepsilon_c \gtrsim 50\mathrm{KeV}$ ($\lambda_c \lesssim 0.25$Å)						
PEP	Stanford	18	165.5	10	78.000	SR Laboratory planned
PETRA	Hamburg	20.5	192	20	99.610	presently not used as SR source
LEP/CERN	Geneva	130	3.410	90	108.900	proposed for high energy physics use

Table 4a: Summary of Parameters describing the National Synchrotron Radiation Light Source (Brookhaven) for a Wiggler in the 2.5 GeV x-ray ring and a bending magnet in the x-ray ring. (From Steenbergen, 1980)

	X-ray (wiggler)	X-ray (arc)
Wavelength (Å)	1	10
[λ_c(Å); ϵ_c(keV)]	[0.5; 25.0]	[2.5; 5.0]
Source dimensions		
$2\sigma_y \times 2\sigma_{x,t}$ (mm^2)	0.035x0.65	0.2 x 0.5
arc length, $\Delta x'$ (mrad)	5	10
vert. opening angle (mrad)($2\sigma'$)	0.3	0.4
Flux, per 0.1% $\Delta\lambda/\lambda$ (ph/s)	10^{14}	2.5×10^{14}
Time structure		
number of bunches	30	30
orbital time (ns)	568	568
effective bunch length (ns)	1.5	1.7
Beam ports, max.	N(N=5)	(28 - N)

Table 4b: Comparison of VUV storage rings.

	ACO (Orsay)	BESSY (Berlin)	NSLS(VUV) (Brookhaven)
Energy E [GeV]	0.55	0.80	0.70
Radius R [m]	1.11	1.83	1.90
Current I [mA]	130	500	1.000
λ_c [Å]	37	20	32
Beam size (FWHM) [μ^2]	1200x1200	240x240	680x260
Flux at λ_c (photons/sec/mrad horiz./ 0.1% bandwidth)	1.14×10^{12}	6.4×10^{12}	1.37×10^{14}
Spectral brilliance (in flux/mm^2/mrad)	6.7×10^{10}	1.37×10^{14}	6.55×10^{13}

Table 5: Comparison of synchrotron radiation source with alternative sources.

Spectral range	Alternative Sources	Remarks
Infrared	Lasers, tunable over limited regions	Laser very much stronger, coherent SR fully tunable
Visible		
Near UV	Lasers gas discharge tubes	for Lasers see Table 7 SR more intense than discharge and fully tunable
Vacuum UV	a few emission lines plasma sources	
Soft x-ray	Characteristic x-ray emission lines	SR more intense (~X1000) and fully tunable
Medium x-ray		
Hard x-ray	Nuclear γ-ray sources	SR from wigglers or multi GeV rings
γ-ray region	Nuclear γ-ray sources	

Table 6: VUV and x-ray radiation sources (from Koch, 1981)

Source	Photon energy range (eV)	Linewidth	Remarks	References
He continuum	$12 \le \hbar\omega \le 21$	-		
Ne continuum	$12.4 \le \hbar\omega \le 16.8$	-	pressures of 50 - 200 torr	
Ar continuum	$8 \le \hbar\omega \le 11.8$	-		
Kr continuum	$6.9 \le \hbar\omega \le 9.9$	-		
Xe continuum	$6.2 \le \hbar\omega \le 8.4$	-		
Hinteregger lamp[a]	$4 \le \hbar\omega \le 14$	multiline		(a),(b)
He I resonance lamp	21.2	∿1 meV ?		
He II resonance lamp	40.8	≤ 10 meV	pressures of 0.1 - 0.5 torr	
Ne I resonance lamp	16.8	∿1 meV		
Ne II resonance lamp	26.9	<10 meV		
Laser generated plasmas				
Yb target				
Sm target	$20 \le \hbar\omega \le 300$ eV	continua		
Cu target		with a few discrete lines of much higher intensity		(c)-(h)
Other targets possible (Al, Te, Fe)				
Electron beam sliding spark (McCorkle Source)	∿300 eV	continuum plus dominant emission in a line at ∿300 eV		(i),(j)
BRV Source	$4 \le \hbar\omega \le 250$ eV	continuum and multiline	10^{-4} torr	(k)
YMξ x-rays	132.3	0.5 eV		
ZrMξ x-rays	151.4	0.8 eV		
NbMξ x-rays	171.4	1.2 eV		
RhMξ x-rays	260.4	4.0 eV		(l),(m)
TiMξ x-rays	452	-		
MgKα x-rays	1254	∿0.7 eV		
Al Kα x-rays	1487	∿0.8 eV		
Cu Kα x-rays	8055	∿2.5 eV		
Nuclear γ-ray sources	50 - 500 KeV several lines	∿1 eV (^{198}Au 411 KeV line)		(n)
Storage ring e.g. DORIS (4 GeV)	$10^{-4} \le \hbar\omega \le 2\times10^{4}$	-	10^{-8} torr	
e.g. PETRA (18 GeV)	$10^{-4} \le \hbar\omega \le 5\times10^{5}$	-	10^{-8} torr	

References for Table 6

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Table 8: Comparison of Pulsed Light Sources (from Munro and Sabersky, 1980)

Characteristic	Synchrotron radiation	Lasers	Incoherent sources
Wavelength range	∿0.1 nm to ∿1 cm	Tuneable over narrow ranges in ultaviolet and visible. Some lines below 200 nm and many in the infrared.	A wide variety of sources are needed to cover the range ∿ 15 nm to radio frequencies.
Intensity (number of photons) per pulse within a 0.1% wavelength band.	$<10^9$	$\sim 10^{10}$ in 1 ps pulse of width $\leq 10 cm^{-1}$	$<10^6$
Minimum approximate pulse duration	100 ps	0.2 ps	$\lesssim 1$ ns
Pulse repetition rate	∿1 to 500 MHz	dc to ∿100 MHz	dc to <100 MHz
Source size and divergence	Incoherent ∿1 mm <10 mrad	Coherent $\gtrsim$ 1 mm $\gtrsim$ 5 mrad	Incoherent ∿few mm isotropic

Table 7: Comparison between VUV Lasers and Synchrotron Radiation Sources (from Koch, 1981)

Source		Energy Region	Linewidth/Resolution	Intensity	Pulse Length	Remarks
ArF laser	(a) (b)	6.41 eV (1933 Å)	10^{-3} eV	$10^{18} - 10^{20}$ photons/pulse	55 nsec	polarized coherent
3rd harmonic mixing in Mg vapor	(c)	8.0 - 9.0 eV (1400-1600 Å)	10^{-5} eV	10^{11} photons/pulse	10 nsec	polarized coherent
discharge pumped F_2 laser	(d)	7.85 eV (1580 Å)	$\leq 3 \times 10^{-3}$ eV	10^{16}	15 nsec	polarized coherent
Present SR sources		$10^{-1} - 3 \times 10^{4}$ eV	10^{-3} eV (0.03 Å) at 5 - 40 eV 10^{-2} eV (0.02 Å) at 40 - 100 eV	$\sim 10^{9} - 10^{13}$ photons/Å sec at 5 - 1000 eV at exit slit	140 psec	polarized not coherent

References:

(a) For rare gas halide lasers in general, see e.g. data sheets by LUMONICS, Ottawa.

(b) Hoffmann et al., Appl. Phys. Letters 28, 538 (1976)

(c) Wallace et al., Appl. Phys. Letters 28, 449 (1976)

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Table 9: Comparison of Cu Kα emission from a rotating anode tube and the continuum from a 100 kW rotating anode with a present day synchrotron source (DCI) and an estimation for the proposed European Synchrotron Radiation Facility ESRF. Note that similar values as for the ESRF hold for radiation from wigglers from the 2,5 GeV NSLS storage ring (Table 4). (From Farge and Duke, 1979.)

	GX6 rotating anode tube 2.4kW (CuKα emission)	DCI 1.72 GeV and 240 mA	ESRF 5 GeV and 565 mA
brightness impact ↑	Small angle scattering with a double monochromator	x 500 to 1.000	x 15.000 to 30.000
	Protein crystallography with a single focus monochromator		
	· 1 mm^3 samples	x 50 to 160	x 900 to 1.800
	· small samples	x 30 to 60	x 650 to 1.300
	Diffuse scattering (wide angles, low resolution and large samples) with a curved graphite monochromator	x 20 to 40	x 160 to 320
Non characteristic wavelength (continuous background) EXAFS experimental set-up sith a 100 kW rotating anode		x 10^4	x 10^5

Figure Captions

Fig. 1 Synchrotron Radiation covers a large part of the electromagnetic spectrum from the microwave range out to the hard x-ray and γ-ray region.

Fig. 2 Experimental uses of the synchrotron radiation spectrum. The unique properties of synchrotron radiation including its broad spectrum extending from the infrared to the x-ray region make it a unique research tool for a broad range of disciplines. It can be useful in any scientific investigation where the structure or nature of a material or specimen can be examined by means of its interaction with electromagnetic radiation. The spectrum graphically illustrates the range of wavelengths available from a typical synchrotron radiation source. Some of the disciplines and research subjects that make use of the synchrotron radiation are also shown, the titles placed to correspond, very approximately, with the part of the spectrum that is utilised (after Lea 1977).

Fig. 3

a) Visible part of synchrotron radiation from the storage ring DORIS.

b) Synchrotron radiation from the storage ring VEPP-3 emerges from a bending magnet through a beam pipe and a Beryllium window. The x-rays ($\lambda<4$Å) are so intense that they ionize the air along their path causing visible fluorescence of the molecules.(Courtesy of Kulipanov).

c) Visible part of synchrotron radiation from the 0.3 GeV SOR storage ring in Tokyo emerges through a window from the extraction chamber. One can clearly see the emission characteristics of synchrotron radiation: within the plane of the storage ring the window is fully illuminated, while the intensity drops rapidly above and below.(Fotograph by E.E. Koch).

Fig. 4 General arrangement of a synchrotron radiation center: L, linear accelerator; B, booster synchrotron; X-SR, x-ray storage ring; VUV-SR, vacuum ultraviolet and soft x-ray storage ring; W, wiggler in a low β insertion; U, undulator; possible radiation fans are indicated.

Fig. 5 Geometry of synchrotron radiation emission; (a) the plane of the accelerator or storage ring is filled with radiation, (b) the intensity in the off plane direction drops rapidly with the increasing angle ψ(bottom). (From Koch 1977).

Fig. 6 General shape of the radiation spectrum of an electron moving in a curved trajectory per GeV.

Fig. 7 Intensity spectra for several storage rings used as synchrotron radiation sources. The parameters for operating the storage rings are the same as given in Fig. 8 (after Thompson and Poole, 1979).

Fig. 8 Average spectral brilliance as a function of wavelength for several different storage rings used as synchrotron radiation sources (after Thompson and Poole, 1979).

Fig. 9 Angular distribution of intensity components with electrical vector parallel ($I_{\parallel}$) and normal ($I_{\perp}$) to the plane of the synchrotron, linear polarization and circular polarization (from decomposition into left (I_L) and right (I_R) hand circularly polarized components) for a storage ring with R = 12.12 m and an energy of E=3.5 GeV (DORIS) calculated for three photon energies $\hbar\omega$. ψ is the elevation angle perpendicular to the orbital plane (after Koch et al. 1976).

Fig. 10 Experimentally determined shape of the light pulses for the storage rings DORIS and for ACO (after Koch et al. 1976).

Fig. 11 A three-pole wiggler with strong central field.

Fig. 12 Description of a planar undulator. A horizontal periodic magnetic field of period λ_o forces electrons to oscillate in the vertical plane with the same period. Instantaneously, the light is emitted in a $1/\lambda$ cone centered on the tangent of the trajectory. θ is the angle of observation. If α is the maximum deflection angle of this trajectory, with the z axis, the nonrelativistic transverse case (K<1) corresponds to $\alpha < 1/\gamma$ and the relativistic one (K> 1) to $\alpha > 1/\gamma$. (From Farge 1980).

Fig. 13 Expected spectral distribution of the light emitted by an undulator in different modes of operation (after Thompson and Poole, 1979): (a) low field case (K << 1); observation through a small pinhole with a very parallel electron beam; (or through a small pinhole, but with a divergent electron beam); (c) high field case (K > 1); observation through a small pinhole with a very parallel electron beam; (d) high field case (K > 1); angular integrated with a very parallel electron beam (or through a small pinhole, but with a divergent electron beam).

Fig. 14 Emission of the Orsay undulator on ACO observed on a white screen with 150-MeV electrons and B_o = 3200 g (K = 1.2). Upper and lower parts of the emission are limited by the size of the vacuum chamber in the ring.(Courtesy of Y. Petroff).

Fig. 15 Observations of SR and UR at Tomsk with a 10λ wiggler set for K = 0.7 for different electron energies and photon polarizations. The first column gives the σ component and the second gives the π component. Different rows correspond to decreasing beam energy going from top to bottom (1-6). The frequency or harmonic number for each spectrum is n = 0.6 (1), 0.8 (2), 1.0 (3), 1.4 (4), 1.8 (5) and 2.0 (6). (Courtesy of M. Nikitin; Tomsk).

Fig. 16 Schematic picture of an electron storage ring with the insertion of a free-electron laser oscillator.

Fig. 17 Synchrotron radiation from 70 MeV Electron Synchrotron at General Electric Research Laboratory, Schenectady, New York, where it was first discovered in 1947.

Fig. 18 Overall layout of the National Synchrotron Light Source, Brookhaven National Laboratory (from Van Steenbergen 1980).

Fig. 19 Plan view of the 2.5 GeV electron storage ring, beam lines and the experimental hall for the Photon Factory at TSUKUBA. L means the location of the long straight sections and M means the medium straight sections (from Huke 1980).

Fig. 20 Outline of the BESSY storage ring (Courtesy of Bradshaw).

Fig. 21 Definitions for describing the characteristics of a light source.

Fig. 22 Phase space ellipses for the vertical coordinate of the electron beam alone (solid lines) and including the SR divergency (dashed lines). The source is located at $Z = 0$, the light beam expands in the positive Z direction. The upright ellipse for SR at $Z = 0$ (a) is sheared while the beam moves to $Z = \ell$(b). The invariants are the intersections with the y-axis, the projection on the y' axis and the area. A slit (with boundaries S_u and S_o) inserted at $Z = \ell$ can be projected back to the origin (a). The shaded area is an invariant also. Figures c and d show the same transformation for an already tilted electron beam ellipse (divergent electron beam!). Similar graphs hold for the horizontal emittance. (From Gudat and Kunz 1979).

Fig. 23 Spectral ranges covered by synchrotron radiation and alternative light sources. The ranges for operating various kinds of monochromators are also indicated (From Koch 1981).

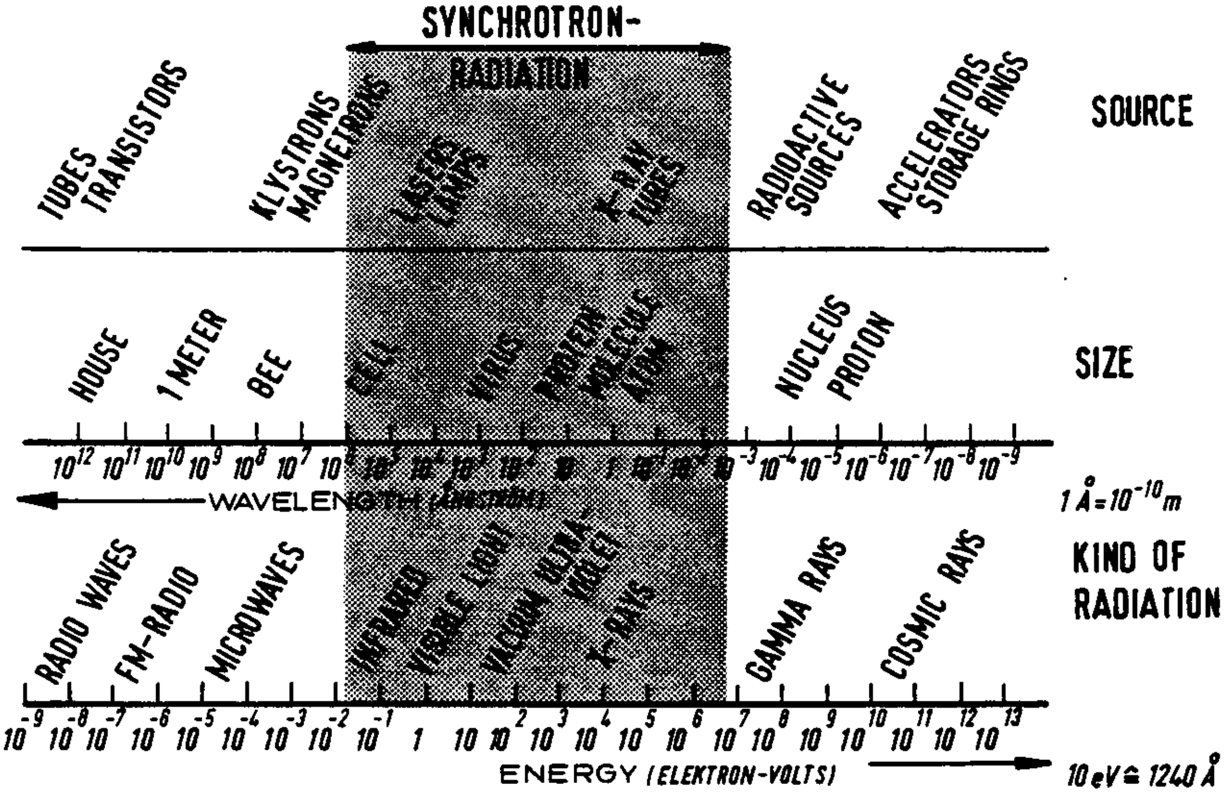
Fig. 24 Schematic spectral distribution of synchrotron radiation with the electron energy in GeV as a parameter. The spectra of rare gas discharge lamps (Tanaka et al., 1958) are shown for comparison. (From Koch 1976).

Fig. 25 Schematic comparison of synchrotron radiation with an x-ray tube with respect to their characteristics in angle, energy and time (after P. Eisenberger, 1974).

Fig. 26 Flux comparison for several x-ray and γ-ray sources. (After Koch and Materlik, 1979).

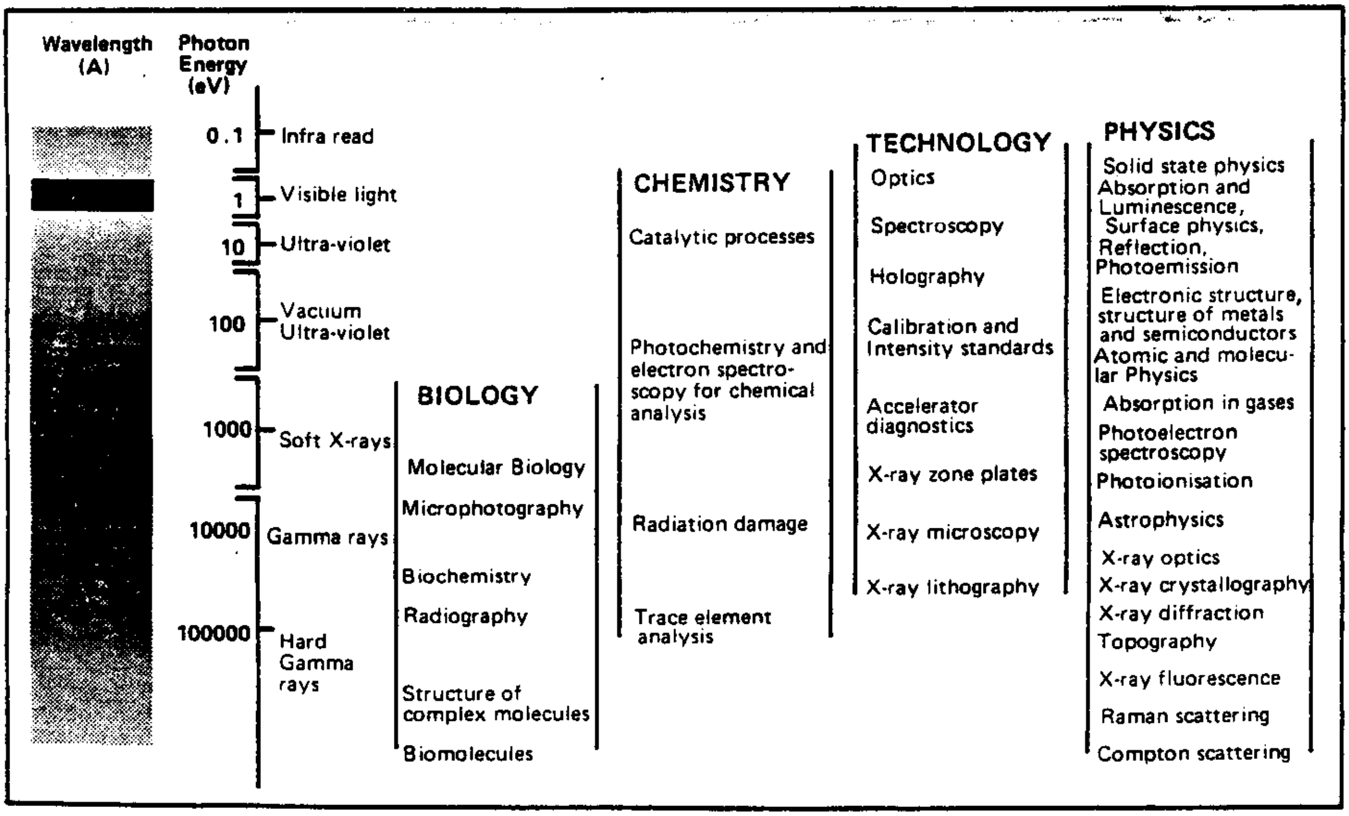
Fig. 27 Upper panel: The interaction of photons with molecules is schematically depicted indicating the many possible spectroscopies. Lower panel: photo-excitation spectroscopies applied to solids and surfaces. Atoms in the outermost surface layer have different geometries and physical properties than the underlying bulk counterparts. Also adsorbed species may be studied by the indicated techniques.

Fig. 28 Schematic representation of the many different x-ray experiments possible with synchrotron radiation.



SYNCHROTRON-
RADIATION
TUBES
TRANSISTORS
KLYSTRONS
MAGNETRONS
LASERS
LAMPS
X-RAY
TUBES
RADIOACTIVE
SOURCES
ACCELERATORS
STORAGE RINGS
SOURCE
HOUSE
1 METER
BEE
CELL
VIRUS
PROTEIN
MOLECULE
ATOM
NUCLEUS
PROTON
SIZE
WAVELENGTH
1 Å=10^-10 m
RADIO WAVES
FM-RADIO
MICROWAVES
INFRARED
VISIBLE LIGHT
VACUUM ULTRA-
VIOLET
X-RAYS
GAMMA RAYS
COSMIC RAYS
KIND OF
RADIATION
ENERGY (ELEKTRON-VOLTS)
10 eV ≙ 1240 Å

Fig. 1



Wavelength (A)
Photon Energy (eV)
0.1 Infra read
1 Visible light
10 Ultra-violet
100 Vacuum Ultra-violet
1000 Soft X-rays
10000 Gamma rays
100000 Hard Gamma rays
BIOLOGY
Molecular Biology
Microphotography
Biochemistry
Radiography
Structure of complex molecules
Biomolecules
CHEMISTRY
Catalytic processes
Photochemistry and electron spectroscopy for chemical analysis
Radiation damage
Trace element analysis
TECHNOLOGY
Optics
Spectroscopy
Holography
Calibration and Intensity standards
Accelerator diagnostics
X-ray zone plates
X-ray microscopy
X-ray lithography
PHYSICS
Solid state physics
Absorption and Luminescence,
Surface physics,
Reflection,
Photoemission
Electronic structure, structure of metals and semiconductors
Atomic and molecular Physics
Absorption in gases
Photoelectron spectroscopy
Photoionisation
Astrophysics
X-ray optics
X-ray crystallography
X-ray diffraction
Topography
X-ray fluorescence
Raman scattering
Compton scattering

Fig. 2

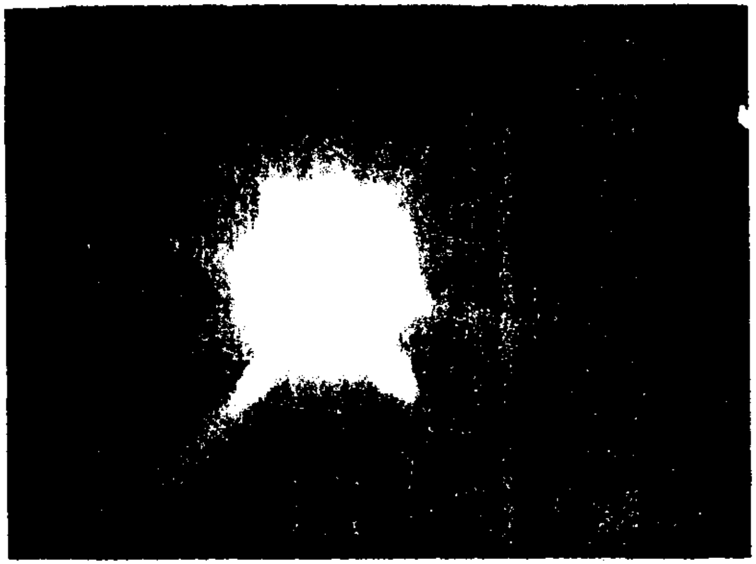


Fig. 3a

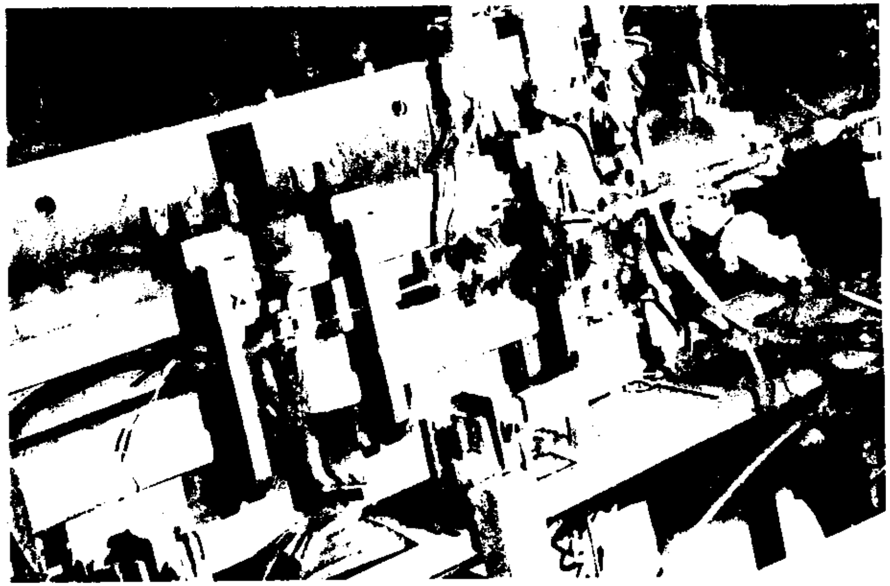


Fig. 3b

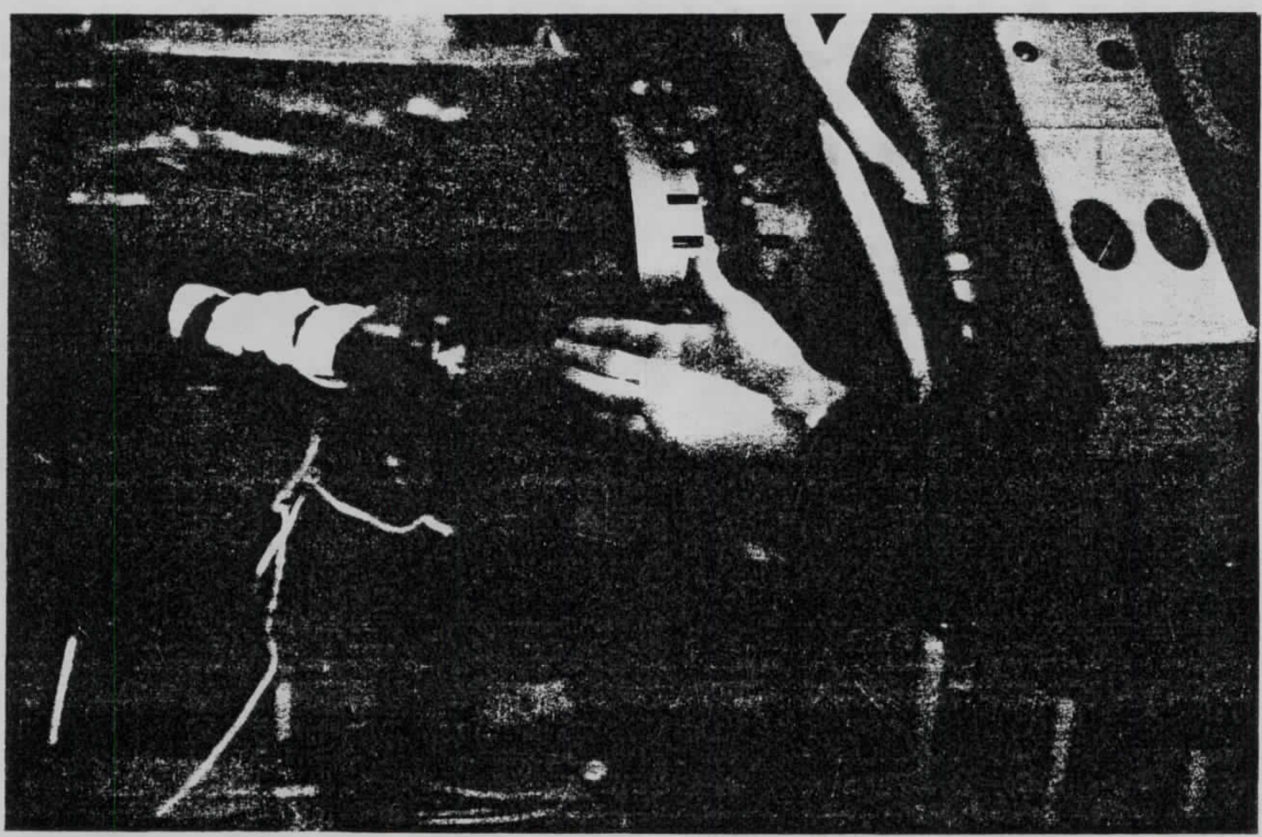


Fig 3c

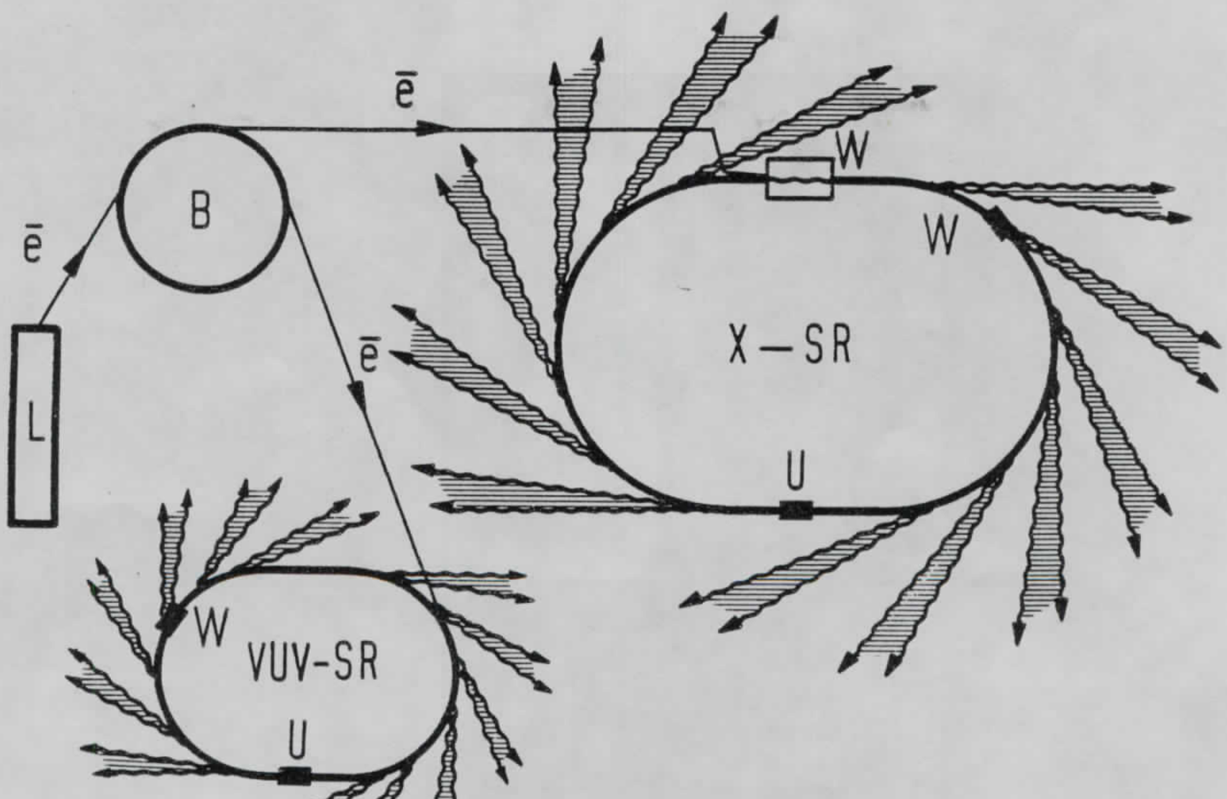
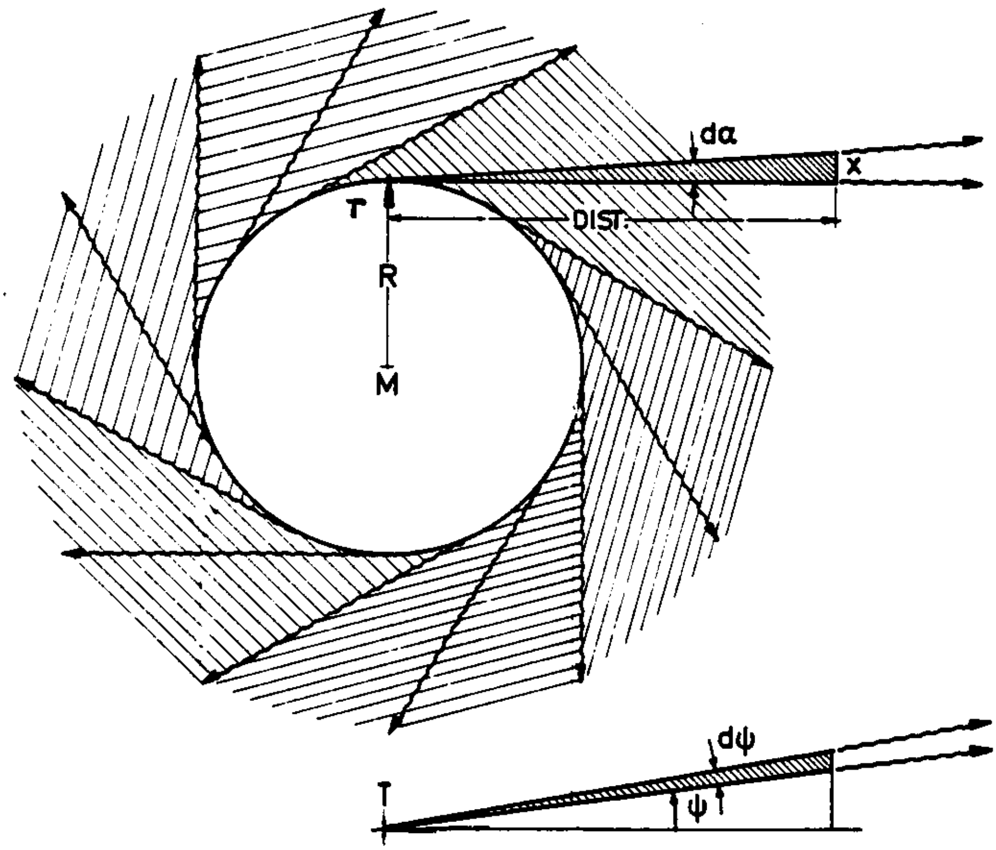
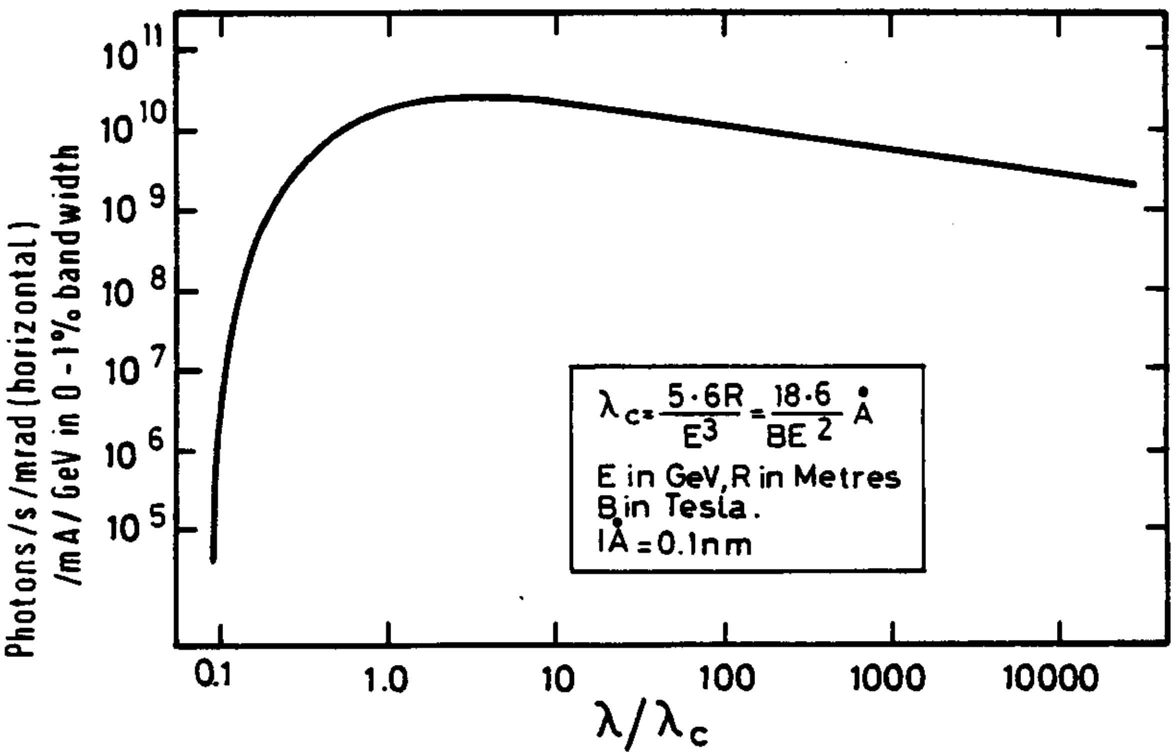


Fig. 4



dα
x
T
DIST.
R
M
dψ
ψ

Fig. 5



Photons/s/mrad (horizontal) /mA/GeV in 0-1% bandwidth
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
0.1
1.0
10
100
1000
10000
λ/λ_c
$\lambda_c = \frac{5\cdot6R}{E^3} = \frac{18\cdot6}{BE^2}$ Å
E in GeV, R in Metres
B in Tesla.
1Å = 0.1nm

Fig. 6

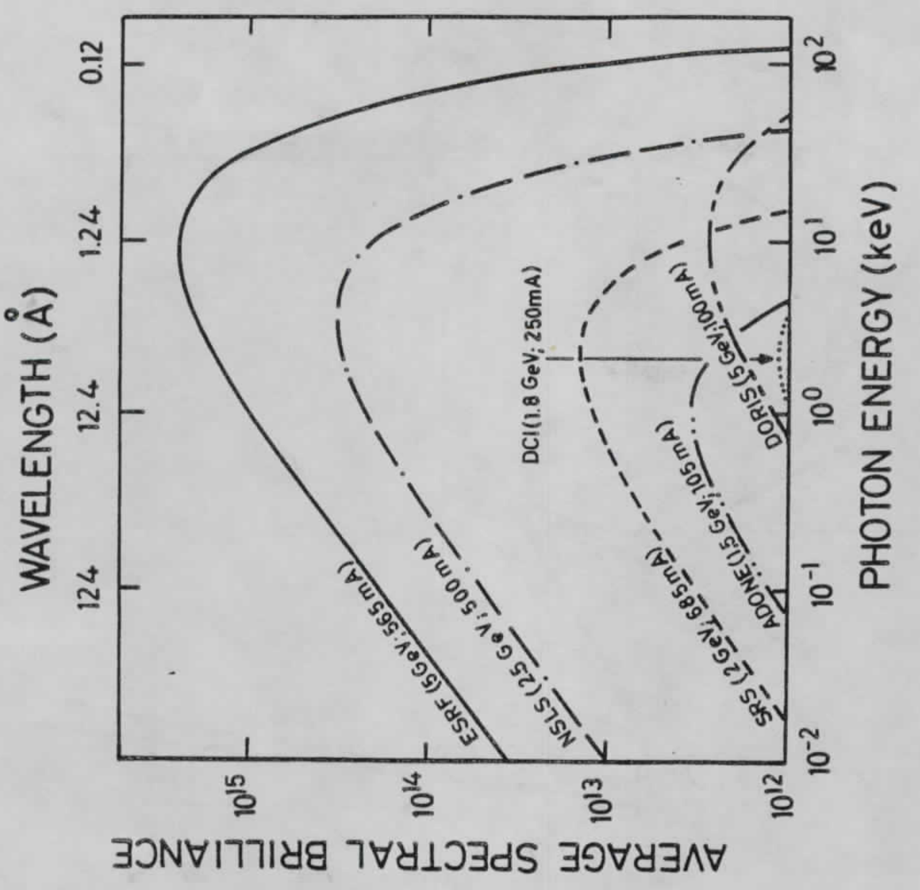

WAVELENGTH (Å)
124
12.4
1.24
0.12
AVERAGE SPECTRAL BRILLIANCE
10^{15}
10^{14}
10^{13}
10^{12}
ESRF (5GeV; 565mA)
NSLS (2.5 GeV; 500 mA)
DCI (1.8 GeV; 250mA)
SRS (2 GeV; 685mA)
ADONE (1.5 GeV; 105 mA)
DORIS (5 GeV; 100mA)
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
PHOTON ENERGY (keV)

Fig. 8

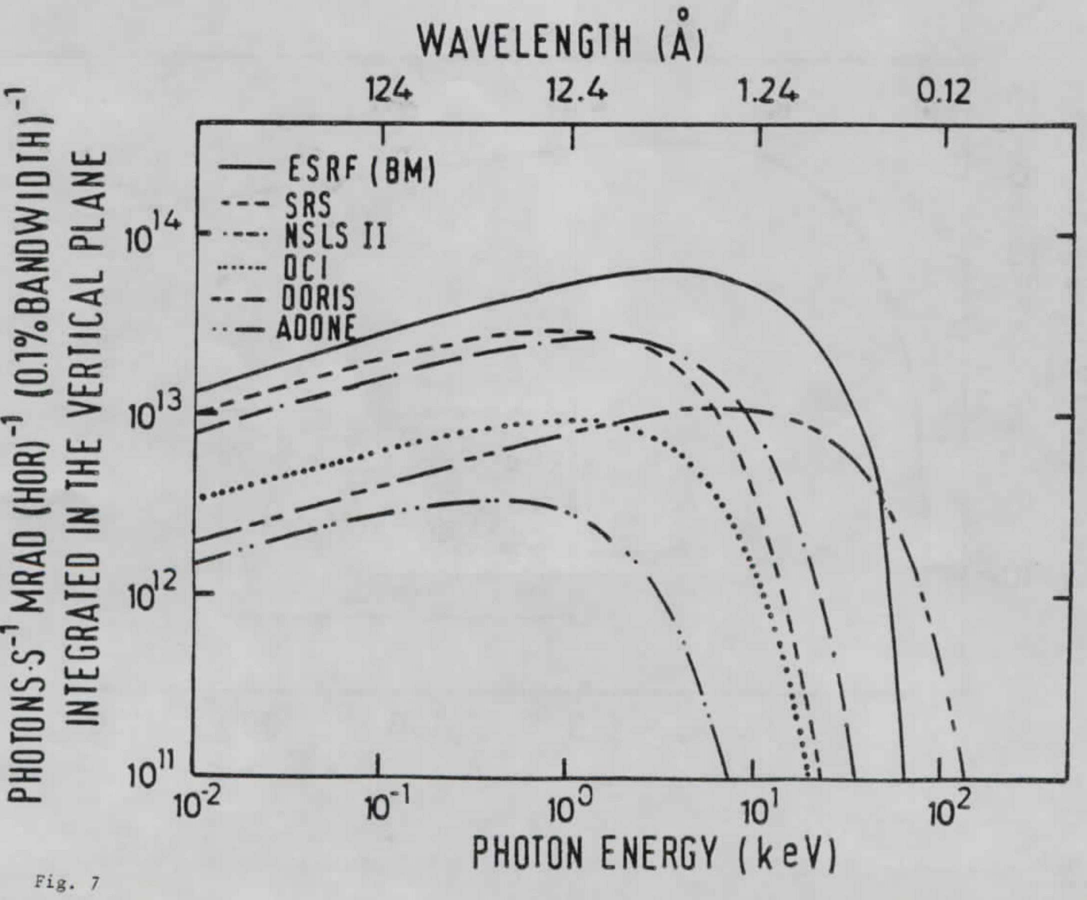

WAVELENGTH (Å)
124
12.4
1.24
0.12
PHOTONS·S^{-1} MRAD (HOR)$^{-1}$ (0.1% BANDWIDTH)$^{-1}$
INTEGRATED IN THE VERTICAL PLANE
ESRF (BM)
SRS
NSLS II
DCI
DORIS
ADONE
10^{14}
10^{13}
10^{12}
10^{11}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
PHOTON ENERGY (keV)

Fig. 7

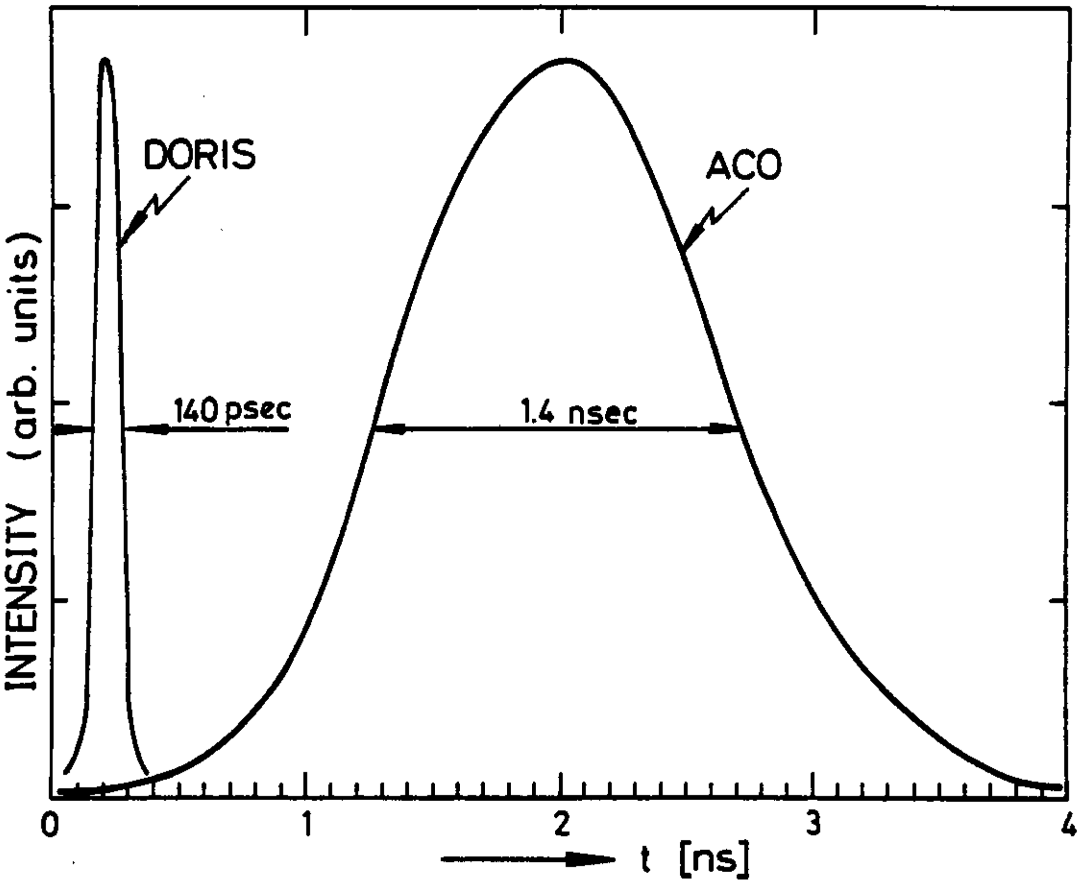

DORIS
ACO
140 psec
1.4 nsec
INTENSITY (arb. units)
0
1
2
3
4
t [ns]

Fig. 10

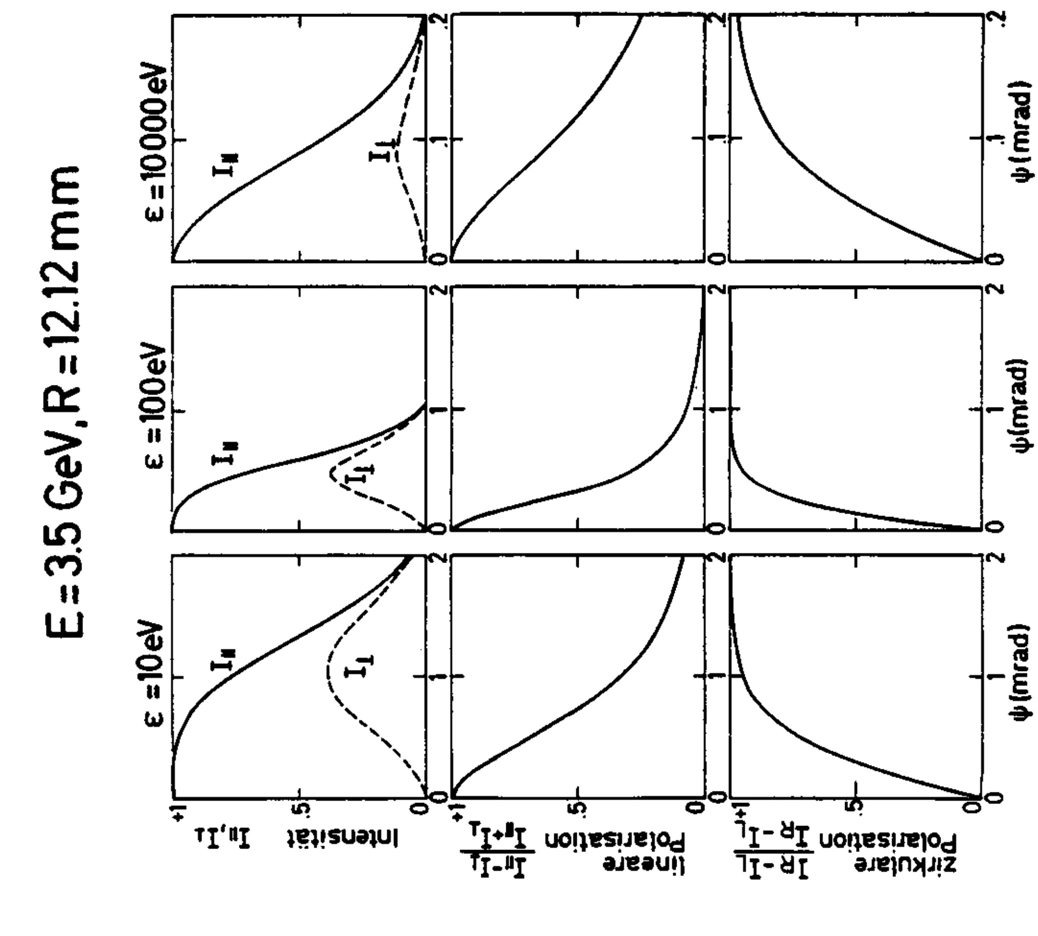

E = 3.5 GeV, R = 12.12 mm
ε = 10eV
ε = 100eV
ε = 10000eV
ψ (mrad)
Intensität
lineare Polarisation
zirkulare Polarisation

Fig. 9

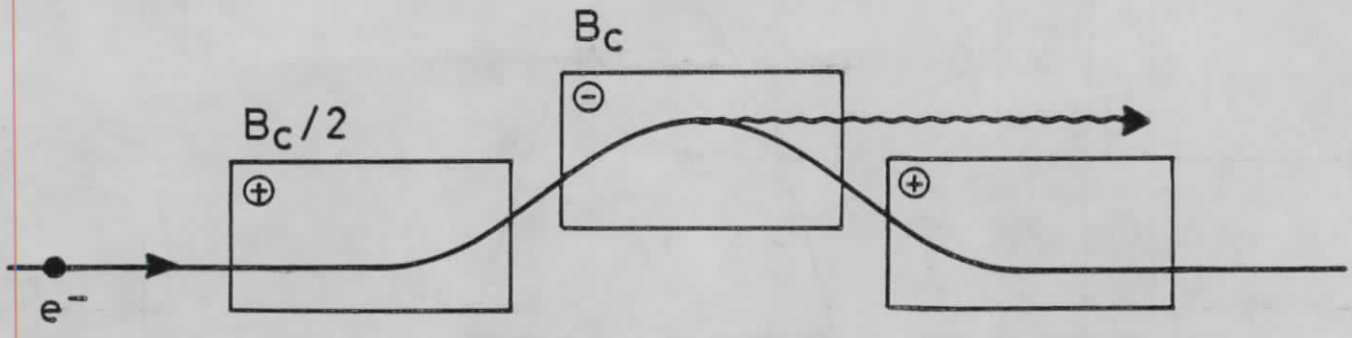


Fig. 11

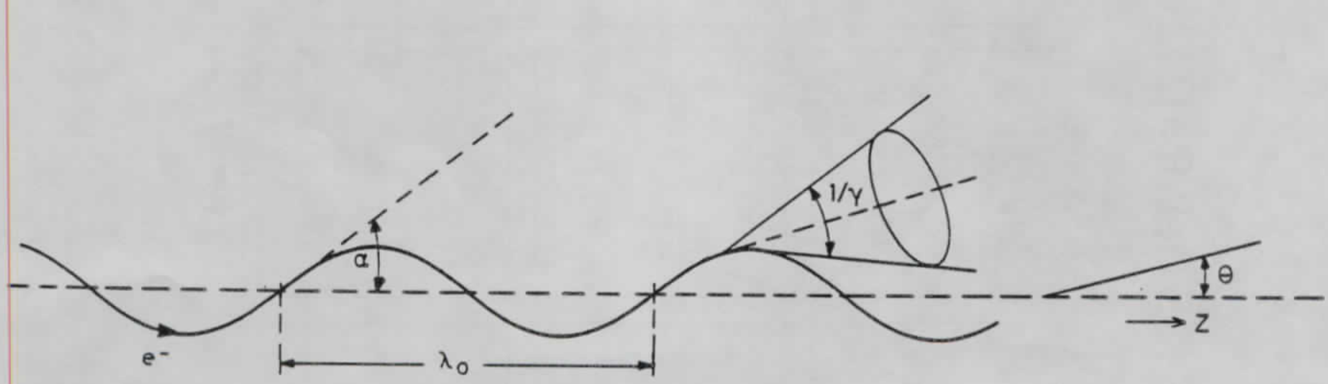


Fig. 12

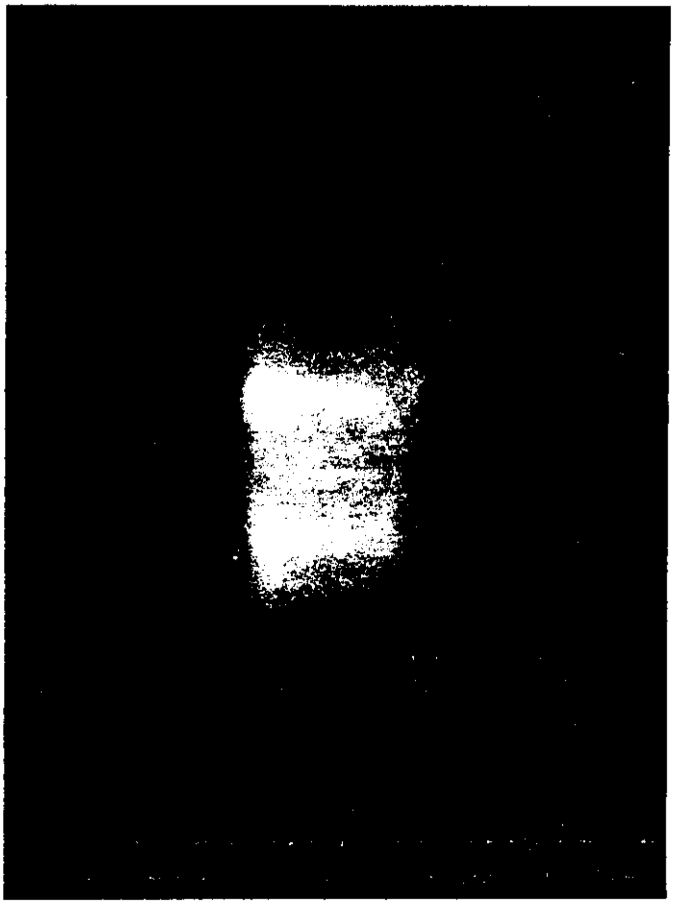


Fig. 14

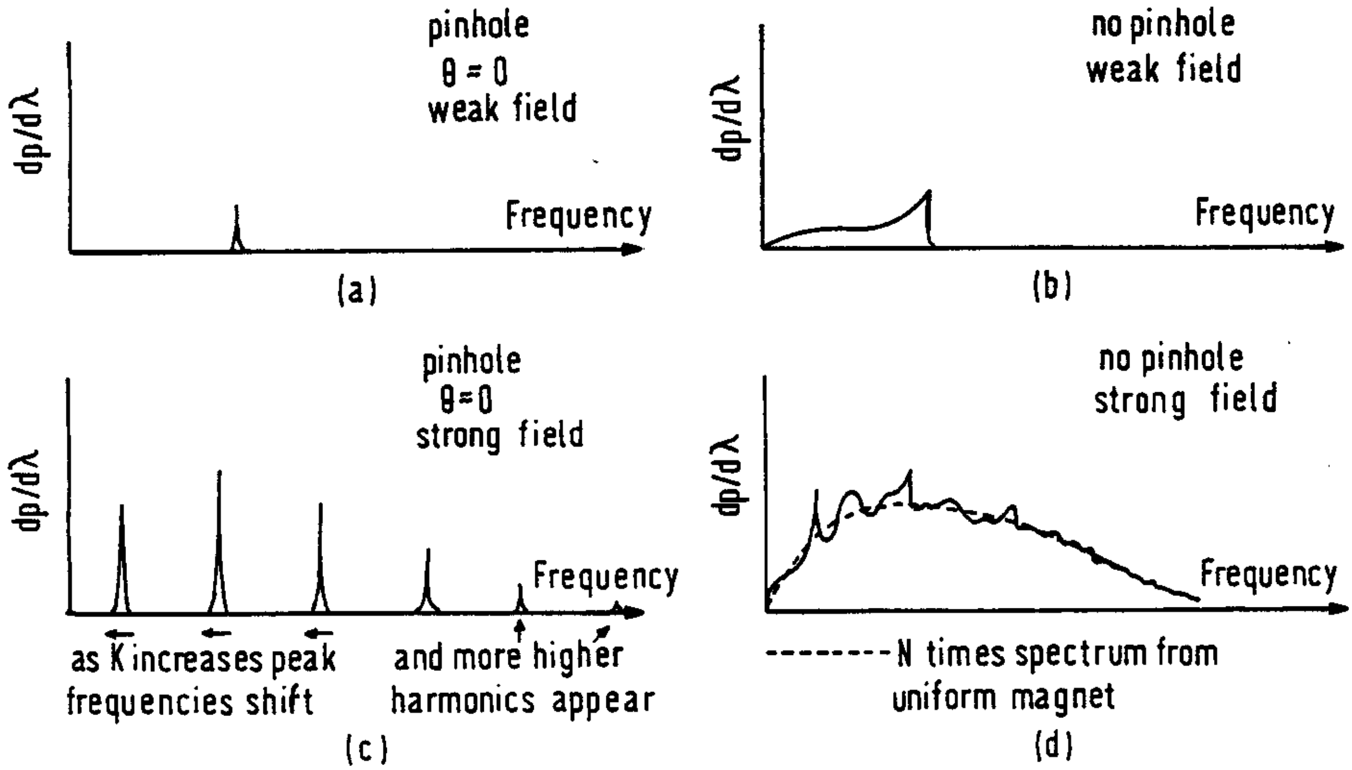

pinhole
θ = 0
weak field
dp/dλ
Frequency
(a)
no pinhole
weak field
dp/dλ
Frequency
(b)
pinhole
θ=0
strong field
dp/dλ
Frequency
as K increases peak
frequencies shift
and more higher
harmonics appear
(c)
no pinhole
strong field
dp/dλ
Frequency
-------N times spectrum from
uniform magnet
(d)

Fig. 13

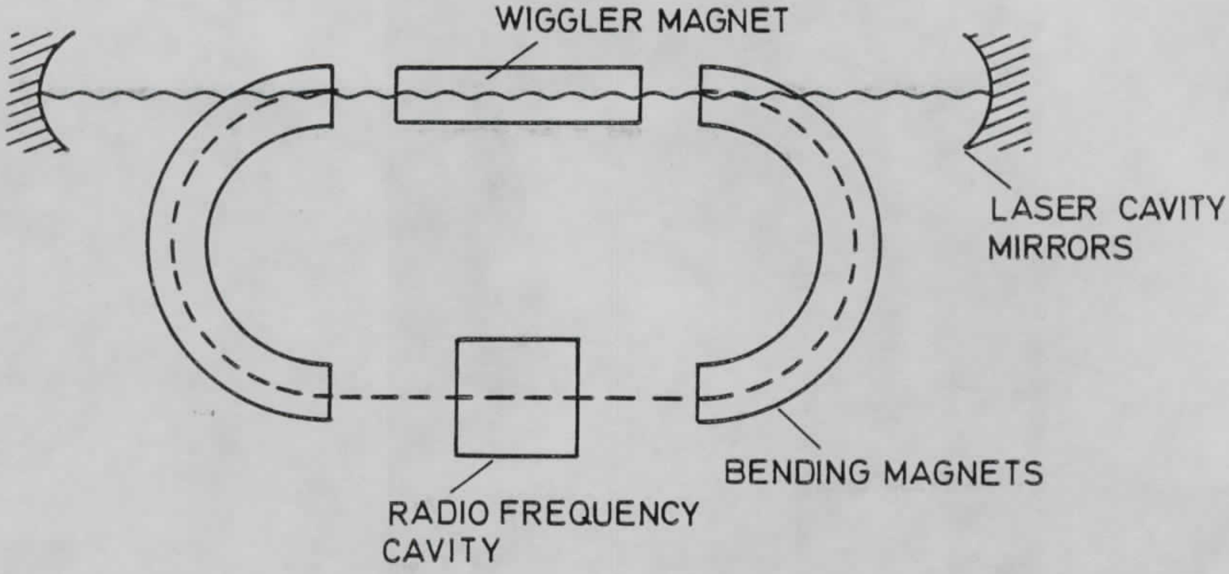

WIGGLER MAGNET
LASER CAVITY
MIRRORS
BENDING MAGNETS
RADIO FREQUENCY
CAVITY

Fig. 16

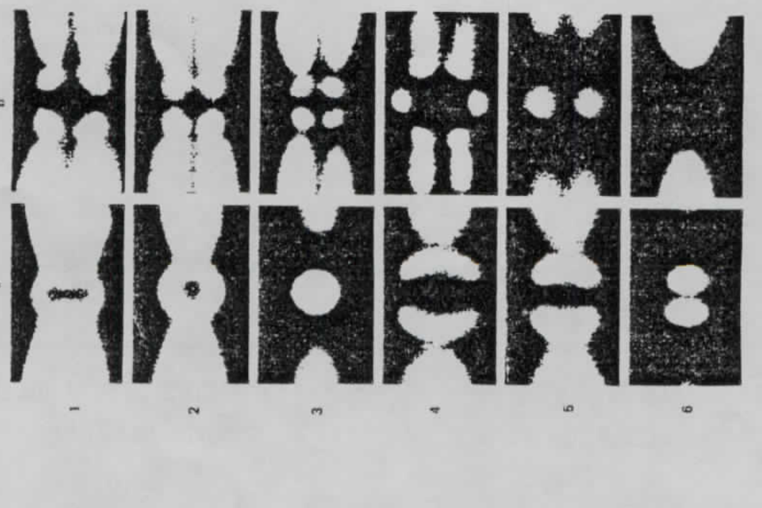


Fig. 15

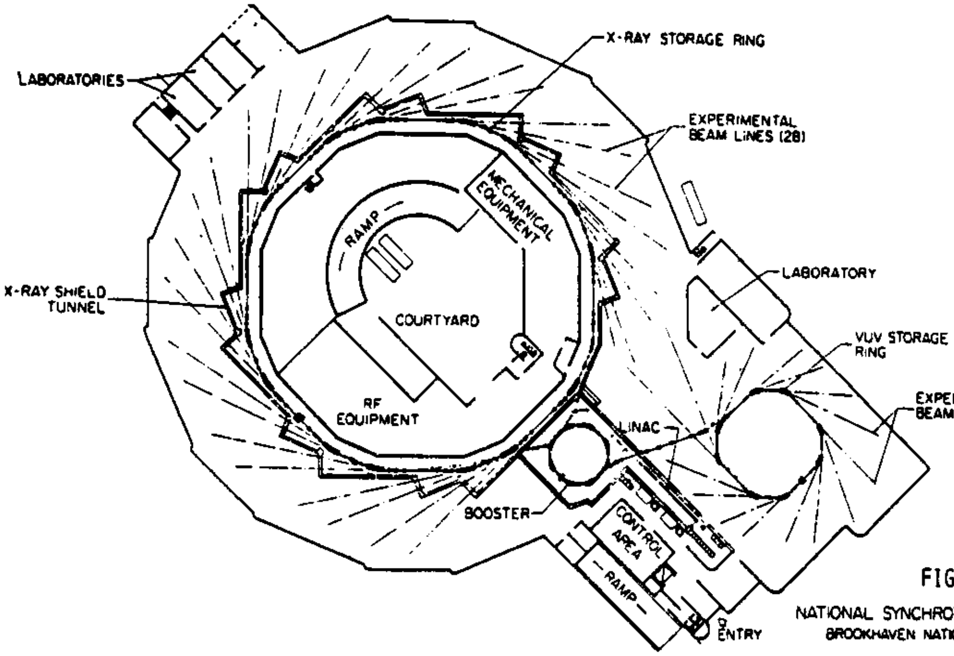


FIG. I

NATIONAL SYNCHROTRON LIGHT SOURCE
BROOKHAVEN NATIONAL LABORATORY

Fig. 18

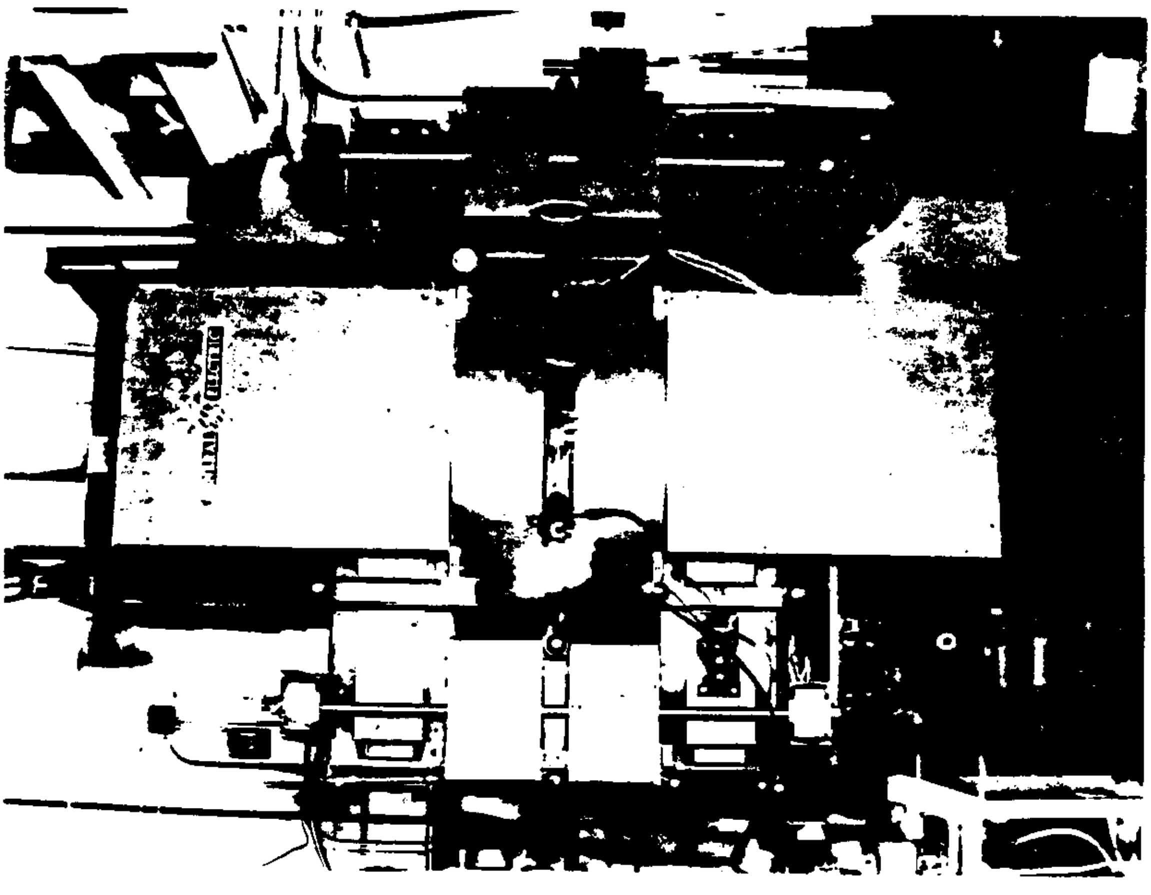


Fig. 17

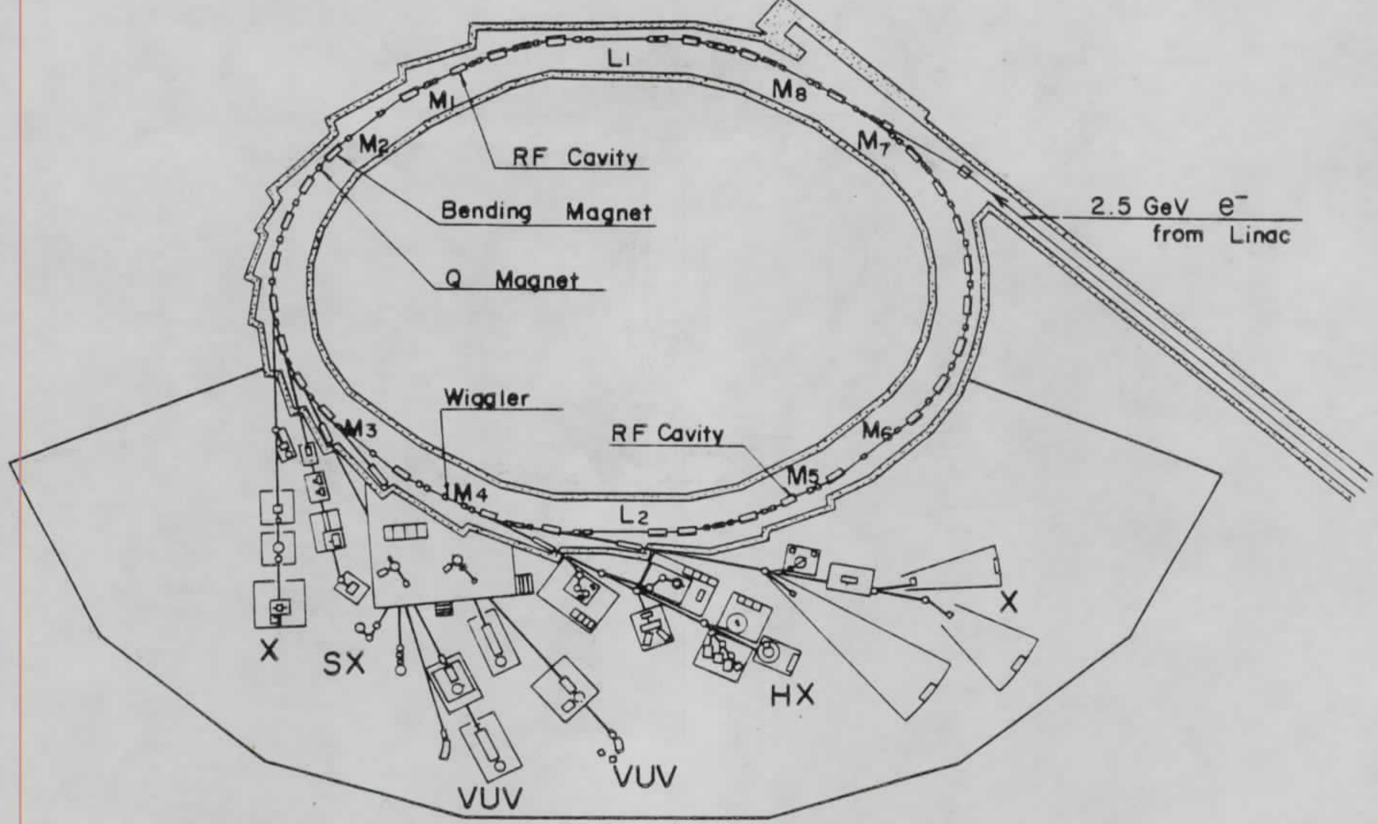

L1
M1
M8
M2
M7
RF Cavity
Bending Magnet
Q Magnet
2.5 GeV e⁻
from Linac
Wiggler
M3
M4
RF Cavity
M5
M6
L2
X
SX
VUV
VUV
HX
X

Fig. 19

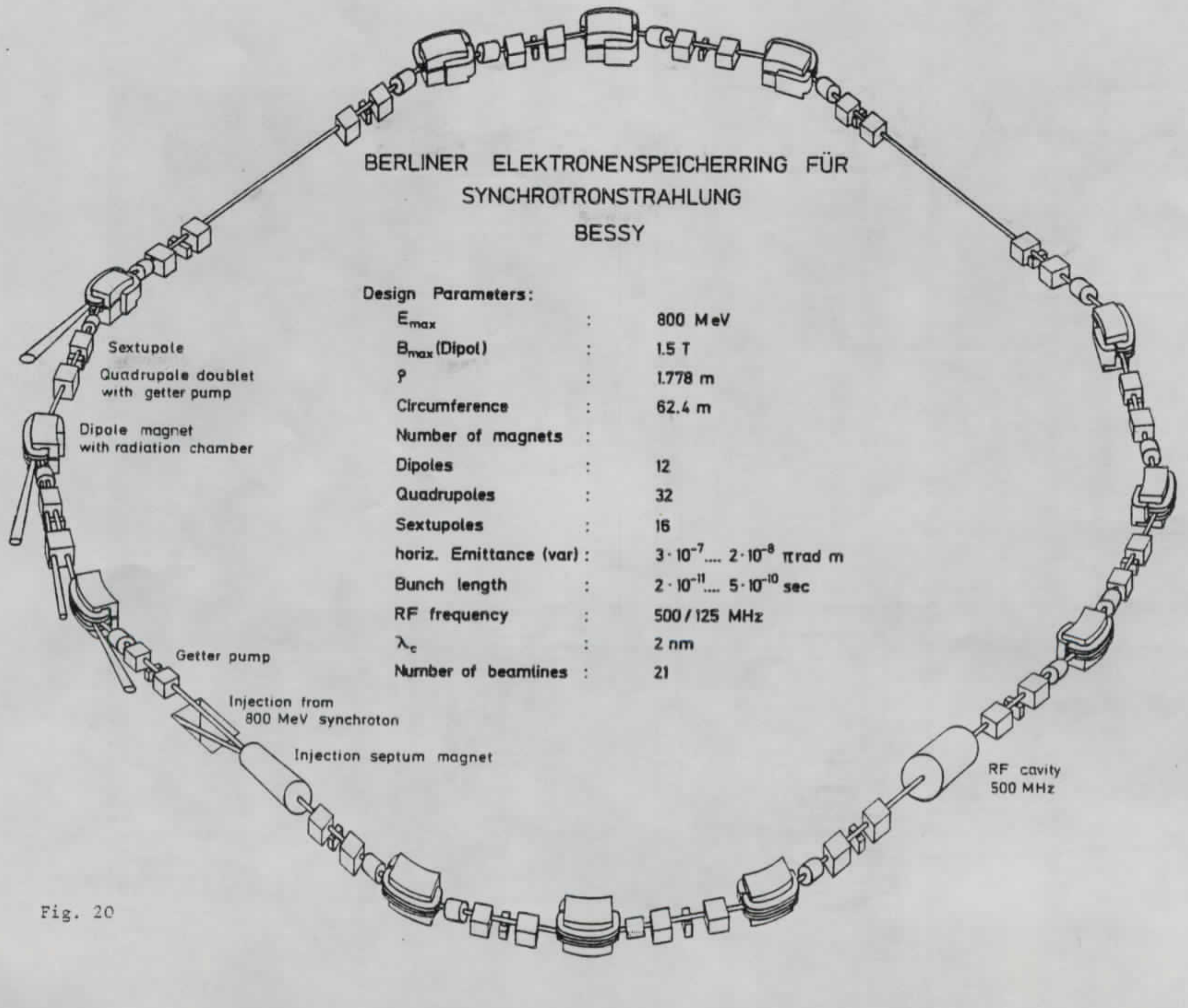

BERLINER ELEKTRONENSPEICHERRING FÜR
SYNCHROTRONSTRAHLUNG
BESSY
Design Parameters:
E_{max} : 800 MeV
B_{max} (Dipol) : 1.5 T
ρ : 1.778 m
Circumference : 62.4 m
Number of magnets :
Dipoles : 12
Quadrupoles : 32
Sextupoles : 16
horiz. Emittance (var) : $3 \cdot 10^{-7}$.... $2 \cdot 10^{-8}$ π rad m
Bunch length : $2 \cdot 10^{-11}$.... $5 \cdot 10^{-10}$ sec
RF frequency : 500 / 125 MHz
λ_c : 2 nm
Number of beamlines : 21
Sextupole
Quadrupole doublet
with getter pump
Dipole magnet
with radiation chamber
Getter pump
Injection from
800 MeV synchroton
Injection septum magnet
RF cavity
500 MHz

Fig. 20

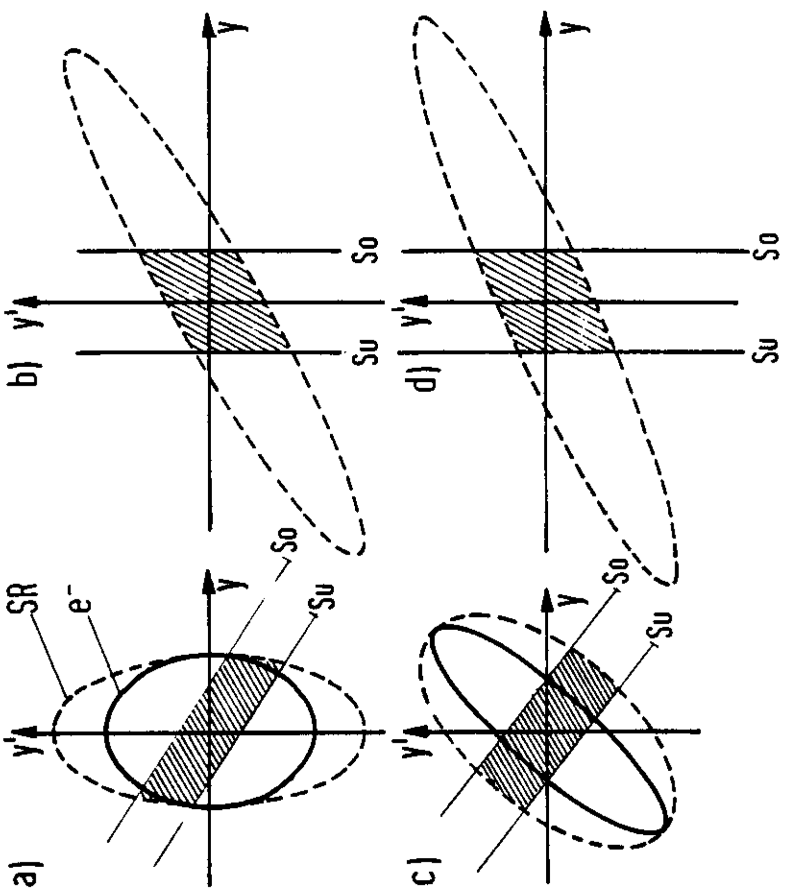

a)
Z=0
y'
y
SR
e⁻
So
Su
b)
Z=l
y'
y
So
Su
c)
y'
y
So
Su
d)
y'
y
So
Su

Fig.22

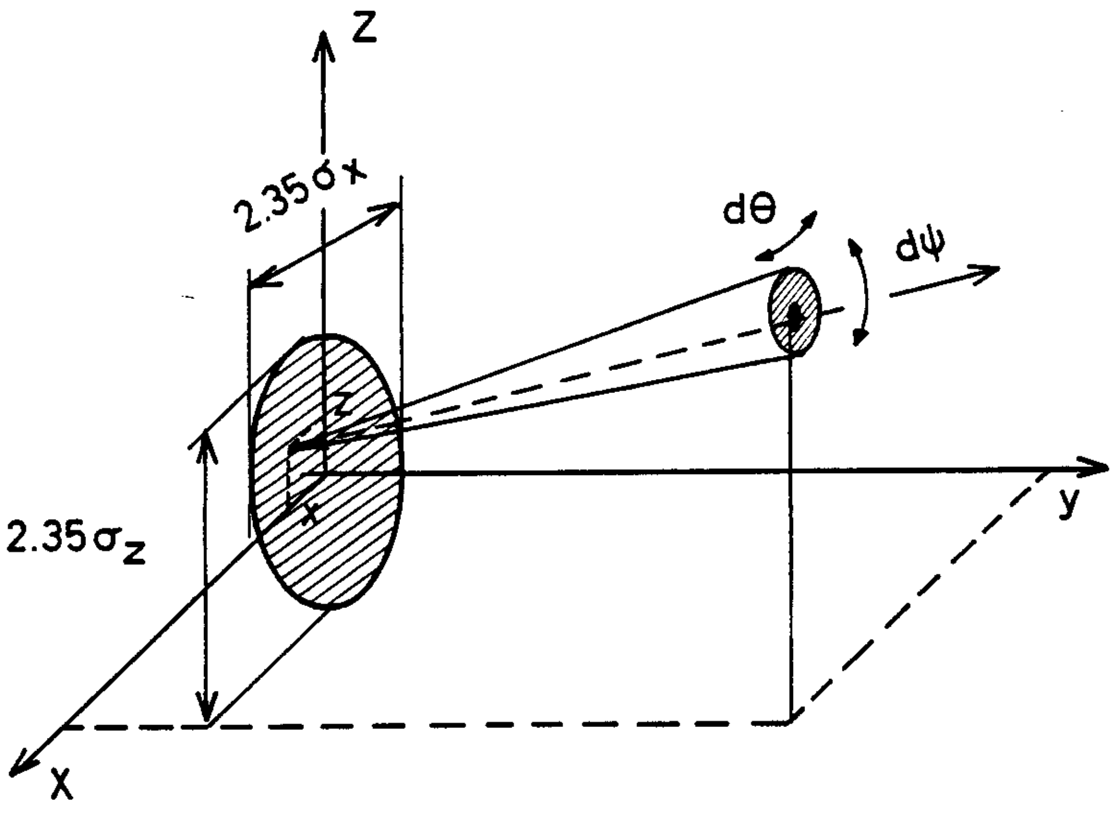

Z
2.35σx
dθ
dψ
2.35σz
y
X

Fig. 21

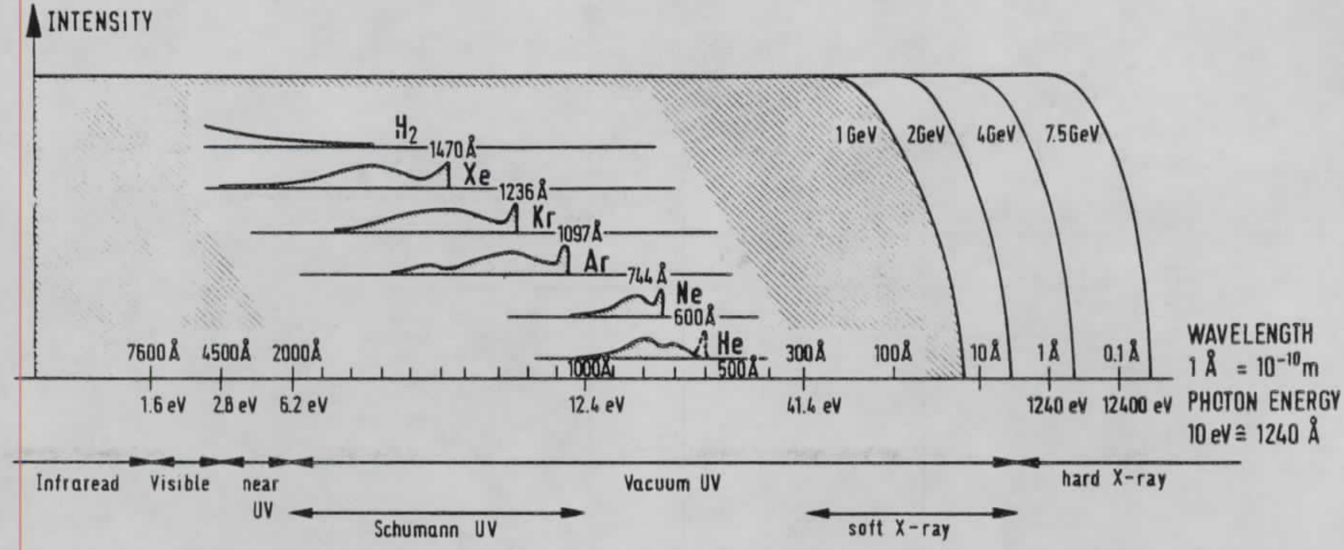

INTENSITY
H_2
1470 Å
Xe
1236 Å
Kr
1097 Å
Ar
744 Å
Ne
600 Å
He
500 Å
1000 Å
1 GeV
2 GeV
4 GeV
7.5 GeV
7600 Å
4500 Å
2000 Å
300 Å
100 Å
10 Å
1 Å
0.1 Å
WAVELENGTH
1 Å = 10^{-10} m
1.6 eV
2.8 eV
6.2 eV
12.4 eV
41.4 eV
1240 eV
12400 eV
PHOTON ENERGY
10 eV ≙ 1240 Å
Infraread
Visible
near UV
Vacuum UV
hard X-ray
Schumann UV
soft X-ray

Fig. 24

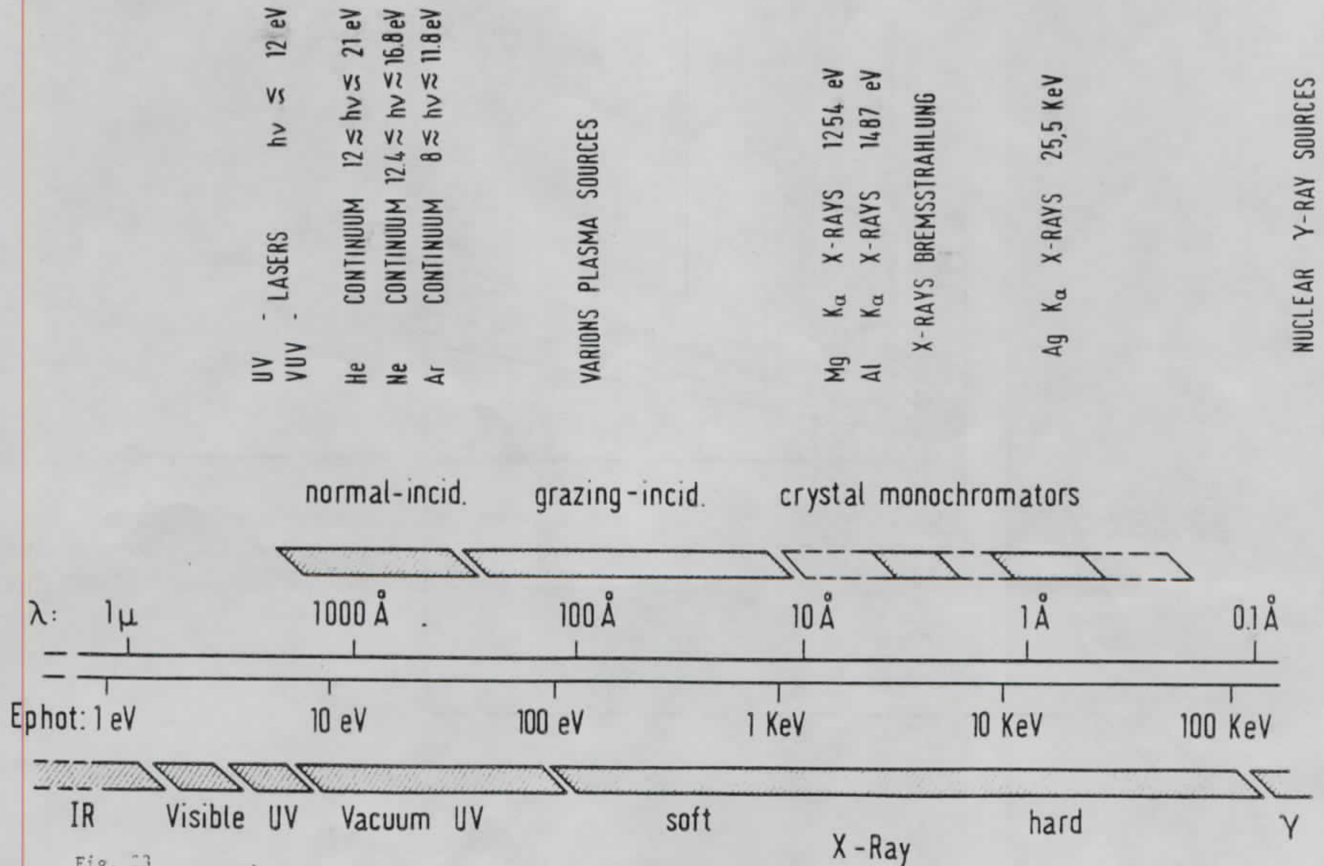
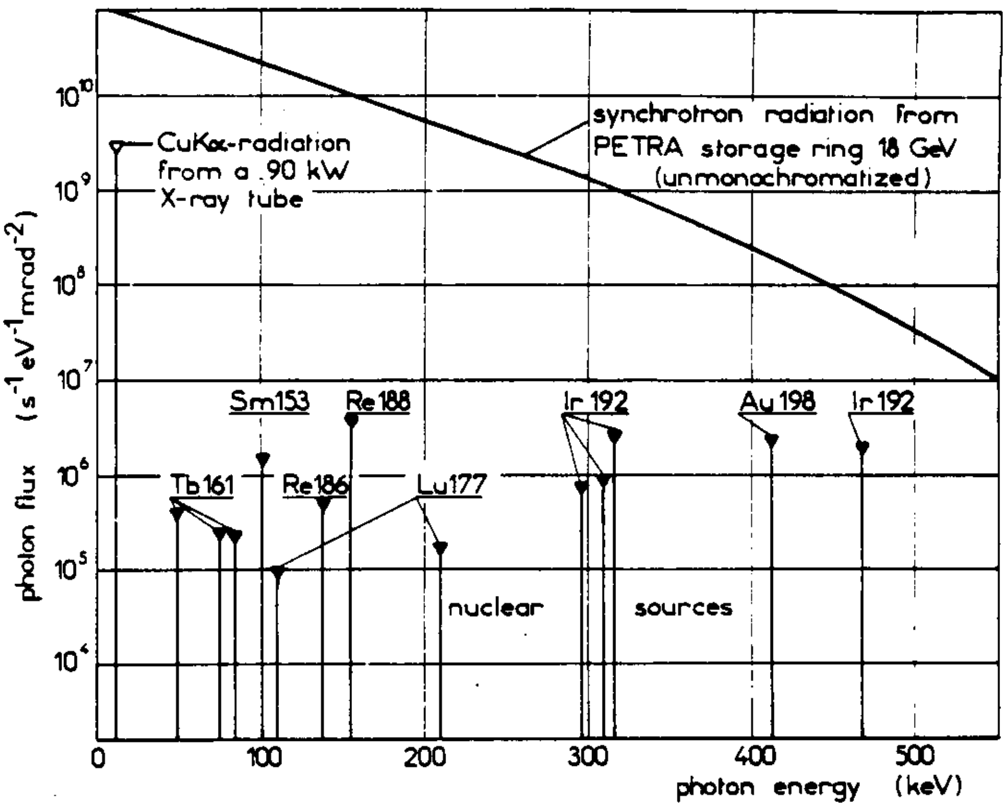
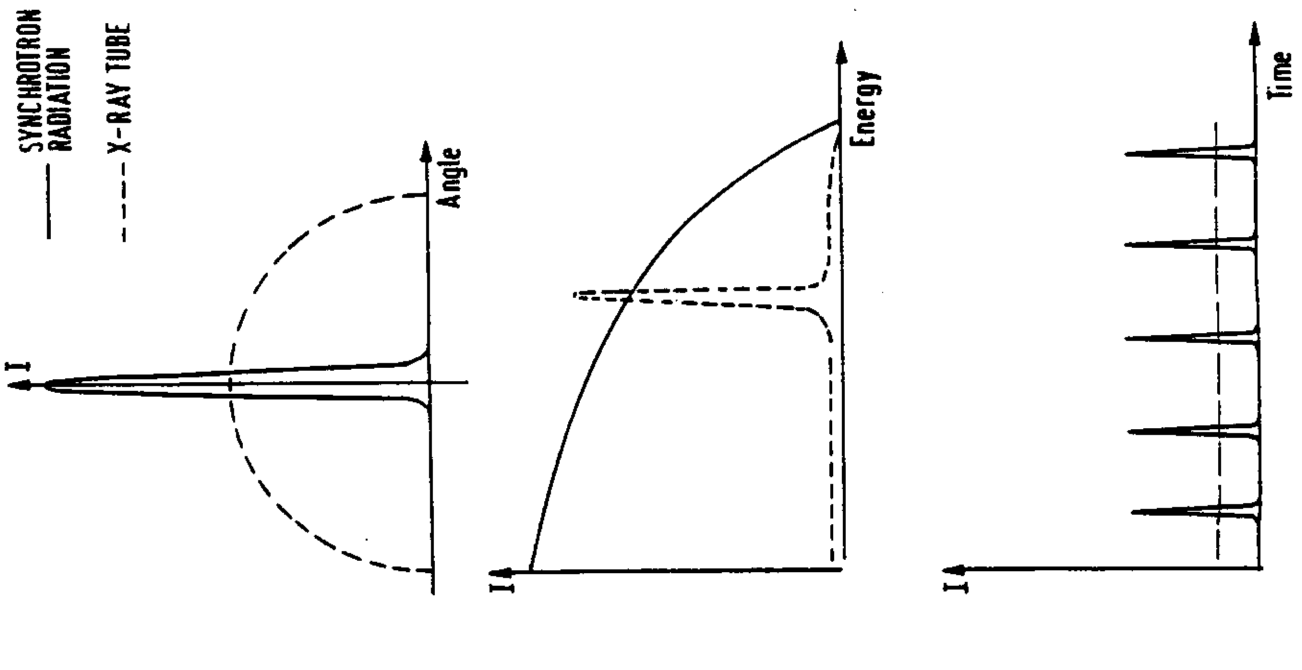

UV - LASERS hν ≤ 12 eV
VUV -
He CONTINUUM 12 ≲ hν ≤ 21 eV
Ne CONTINUUM 12.4 ≲ hν ≲ 16.8 eV
Ar CONTINUUM 8 ≲ hν ≲ 11.8 eV
VARIONS PLASMA SOURCES
Mg K_α X-RAYS 1254 eV
Al K_α X-RAYS 1487 eV
X-RAYS BREMSSTRAHLUNG
Ag K_α X-RAYS 25,5 KeV
NUCLEAR Y-RAY SOURCES
normal-incid.
grazing-incid.
crystal monochromators
λ: 1μ
1000 Å
100 Å
10 Å
1 Å
0.1 Å
Ephot: 1 eV
10 eV
100 eV
1 KeV
10 KeV
100 KeV
IR
Visible
UV
Vacuum UV
soft
hard
X-Ray
γ

Fig. 23



synchrotron radiation from
PETRA storage ring 18 GeV
(unmonochromatized)
CuKα-radiation
from a 90 kW
X-ray tube
photon flux (s^{-1}eV^{-1}mrad^{-2})
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
Sm153
Re188
Ir 192
Au 198
Ir 192
Tb161
Re186
Lu177
nuclear sources
0
100
200
300
400
500
photon energy (keV)

Fig.2:



SYNCHROTRON RADIATION
X-RAY TUBE
Angle
Energy
Time
I
I
I

Fig. 25

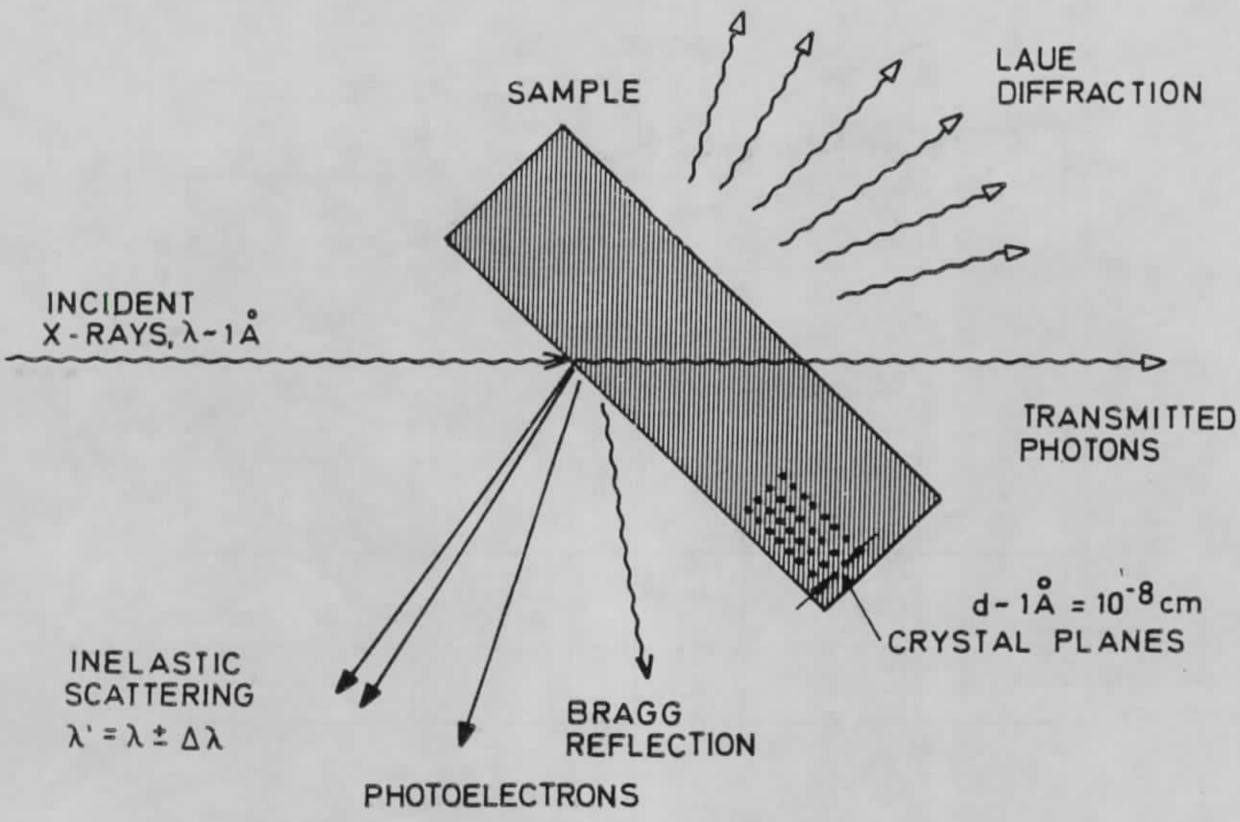

SAMPLE
LAUE
DIFFRACTION
INCIDENT
X-RAYS, λ~1Å
TRANSMITTED
PHOTONS
d~1Å = 10^-8 cm
CRYSTAL PLANES
INELASTIC
SCATTERING
λ' = λ ± Δλ
BRAGG
REFLECTION
PHOTOELECTRONS

Fig. 28

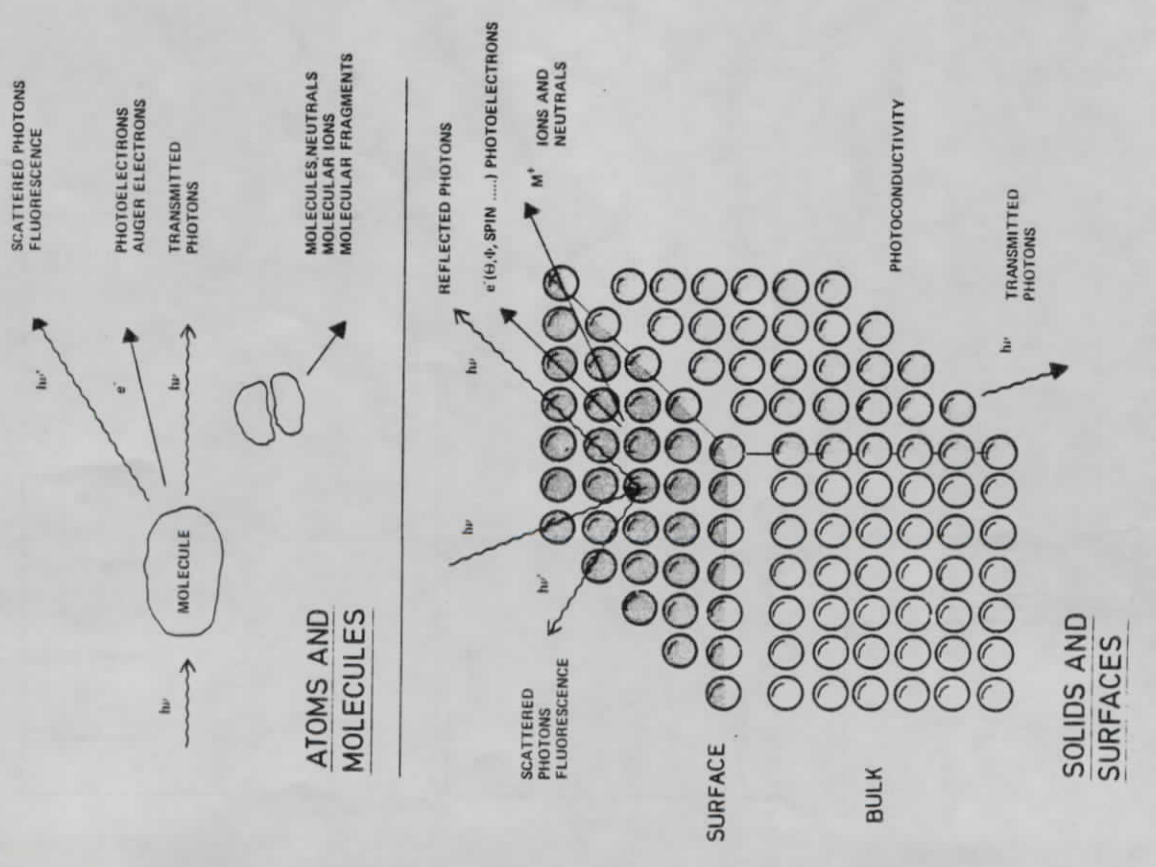

SCATTERED PHOTONS
FLUORESCENCE
PHOTOELECTRONS
AUGER ELECTRONS
TRANSMITTED
PHOTONS
MOLECULES,NEUTRALS
MOLECULAR IONS
MOLECULAR FRAGMENTS
MOLECULE
ATOMS AND
MOLECULES
REFLECTED PHOTONS
PHOTOELECTRONS
IONS AND
NEUTRALS
PHOTOCONDUCTIVITY
TRANSMITTED
PHOTONS
SCATTERED
PHOTONS
FLUORESCENCE
SURFACE
BULK
SOLIDS AND
SURFACES

Fig. 27