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Synchrotron Radiation
Introduction and Properties

by

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SYNCHROTRON RADIATION

INTRODUCTION AND PROPERTIES

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1. Introduction - Properties of synchrotron radiation

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Synchrotron radiation (SR) is electromagnetic radiation emitted by charged particles moving on circular orbits with highly relativistic velocities. In present day's accelerators and storage rings only the lightest charged particles, electrons and positrons, have a velocity sufficiently near to the velocity of light, c, to give off SR with an intensity of practical importance. Not only synchrotrons but also betatrons, storage rings and any bending magnet in a particle beam line can be a source of SR, the name originates from the fact that its first observation was made at the General Electric synchrotron in Schenectady (USA) in 1946. It is sometimes also called "magnetic bremsstrahlung".

Synchrotron radiation originally was just one of the by-products of high-energy particle accleration. When the accelerators became larger SR turned out to be the main mechanism for energy loss and an appreciable fraction of the microwave power fed to the accelerator cavities is needed to compensate this loss. On the other side the damping mechanism of beam oscillations brought about by SR in storage rings is a positive aspect for accelerator technology, e.g. for the injection procedure.

The mechanism of SR emission is comparable to that of an oscillating dipole, which is the picture one obtains when projecting the circular orbit sideways. The intensity, however, is not confined to the fundamental frequency of revolution which is in the MHz range but due to the δ-function like concentration of charge at the particle and due to the relativistic velocities harmonics contribute up to very high order. The spectrum emitted extends from the visible through the vacuum-ultraviolet, soft x-ray range far into the x-ray range proper (see Fig. 1.1). The individual harmonic lines are smeared out thus leading to a continuous spectrum. The following outstanding properties make SR one of the most useful sources for spectroscopy at photon energies above the visible:

1. Continuous spectrum from the infrared to the x-ray region,
2. collimation of the emitted radiation in the instantaneous direction of flight of the emitting particles (angular spread is in the order of 1 mrad),
3. linear polarization with the electric vector parallel to the plane of the orbit,
4. circular polarization above and below the plane of the orbit,
5. time structure with pulse lengths down to 100 psec,
6. absolute calculability of all the properties of the source
7. cleanliness of the source since light emission takes place in ultrahigh vacuum in contrast to gas discharge or spark lamps.

It is, however, necessary to point out that any highpower laser in its regime surpasses SR in spectral brightness. While a laser has all its power concentrated in a narrow spectral range the large power of synchrotron radiation is spread out over an enormous spectral range in most of which no laser sources yet exist. On the other hand the recent ideas about SR emission from beams with sinusoidally oscillating paths, so called periodic wigglers, can lead to a spectral concentration of SR, if not to a free electron laser in the vacuum ultraviolet or x-ray regions.

Before synchrotron radiation can profitably be applied monochromatization is necessary in most of the cases. A thorough quantitative knowledge of all its properties is needed for the construction of a good instrumentation. After a short historical review in section 1.1 a quantitative treatment of the SR properties is given in section 1.2. While the advantages of SR over classical sources in practically all respects is quite clear in the vacuum ultraviolet region (6 eV - 6 keV), a detailed comparison has to be made for each experiment in the x-ray region. These considerations will be discussed in section 1.3. The references of this chapter are mainly concerned with the basic facts about SR while reviews and papers on instrumentation and applications are cited in the corresponding other chapters.

1.1 Historical development

While IVANENKO and POMERANCHUK (1944) (1.1) and independently somewhat later SCHWINGER (1946) (1.2, 1.3) were the first who worked out the theory of SR for circular particle accelerators, its origin can be traced back to the end of the nineteenth century. LIENARD (1.4) and SCHOTT (1.5-1.7) showed that an electron moving on a circular orbit is a strong source of electromagnetic radiation. SCHOTT's work was initially an attempt to create a classical model of the stable atom. Quantization of angular momentum, which solved the problems of the nonradiating atom is a negligible ingredience for the huge "quantum orbits" with 1 - 1000 m diameter in present day's synchrotrons and storage rings. It was shown that quantum mechanical corrections are usually not larger than 10^{-5} (1.3, 1.8-1.11). Subsequently to the pioneering theoretical papers practically all aspects of SR emission were clarified (1.12-1.31). The only aspect of SR which may need some further considerations is that of coherence although there have been several treatments concerned with special questions (1.13, 1.29-1.31).

The first experimental observation of SR is very illustratively discussed in a letter in Physics Today in 1975 by BALDWIN (1.32). BLEWETT (1.33) was the first experimentalist who became interested in observing SR. In 1946 he measured (1.33) the energy loss due to SR in a betatron as a contraction of the orbit. Since this was a 100 MeV betatron he would have been able also to "see" SR if the vacuum system had not been made out of black ceramics. BLEWETT looked for an emission in the microwave region without success. One year later a technical assistant (FLOYD HABER) (1.32) working at one of the first synchrotrons, the 70 MeV General Electric machine, was the first man to "see" SR with the help of a mirror. This observation was correctly explained and published by ELDER et al. (1.34).

Thereafter the properties of SR were studied systematically at several places (1.35-1.55) in addition to the 70 MeV synchrotron in Schenectady, namely the 250 MeV synchrotron in Moscow, the 300 MeV synchrotron at the Cornell University, the 180 MeV synchrotron at the NBS in Washington, and the 6 GeV synchrotron DESY in Hamburg. The increasing size of these machines is depicted in Fig. 1.2.

TOMBOULIAN and co-workers were the first to demonstrate the feasibility to do useful spectroscopy in the vacuum ultraviolet with SR (1.44) at Cornell while this was exploited systematically for the first time from 1961 on by MADDEN and CODLING (1.47 - 1.50) at the NBS predominantly for clarifying the absorption behaviour of rare gases in the vacuum ultraviolet.

It is interesting to ask the question why it took a fairly long time from the first observation of SR to its useful and systematic application. There are probably two reasons, the first is the relative complexity of this light source compared to what spectroscopists were used before, and the second reason has its origin in the fact that up to very recently practically all the accelerators and storage rings producing SR were in the hands of high energy particle physicists and were optimized and scheduled according to their needs. Long term prospectives looked reliable only at a few places in order to attract spectroscopists to make a long term investment. It took another 15 years after 1960 before the first storage ring designed and built specifically as a light source went into operation (1.56). Although our present day's storage ring sources would not have been developed to such high standards without the enormous potential of high-energy physics and although the quality of their machines is not so different from what is ideal for spectroscopy the large expansion of SR came only with the advent of the idea of storage rings dedicated to SR work.

From 1960-1970 several larger centers developed at places where favorable conditions were found: NBS, Washington (1.50), INS, Tokyo (1.57,58), DESY, Hamburg (1.55) this was augmented by a few smaller activities like the ones in Bonn and Frascati. Only after about 1970 TANTALUS in Stoughton, Wisconsin (1.59-61), as the first storage ring, not built, but operated exclusively for SR work, came into full operation. After 1974 the same conditions became true for ACO at Orsay (1.62). 1976 the 300 MeV INS-SOR storage ring in Tokyo (1.56) went into operation, the first ring designed as a light source. At about the same time SURF II at the NBS, Washington, came into life (1.63). Of the large storage rings presently available we want to mention especially VEPP 2M and VEPP 3 at Novosibirsk (1.64), SPEAR at Stanford (1.65) and DORIS at Hamburg (1.66). The latter two have expansion programs underway which are described in (1.67,68) for DORIS and in (1.65) for SPEAR. Further expansions of the laboratory are planned for ADONE at Frascati. New dedicated storage rings are under preparation with SRS at Daresbury (1.69), ALADDIN at Stoughton (1.70), two storage rings at the National Synchrotron Light Source Center at Brookhaven (1.71), PAMPUS in Amsterdam (1.72), the Photon Factory project in Japan and a small storage ring in Berlin. Several more dedicated storage rings are proposed all over the world, especially for industrial applications, and several studies on future needs have been prepared (1.72'). Tables 1.1 and 1.2 give a compilation of all the machines which are operated or planned as SR sources, see also (1.73). The SRS and BROOKHAVEN II machines will install wiggles at high magnetic fields to shift ε_c far beyond the values given in Table 1.2. Many further references from the early days of SR can be found in a bibliography by MARR et al. (1.74).

1.2 Quantitative Properties

1.2.1 Equations for Ideal Orbits

The derivation of the fundamental equations describing the emission of SR can be found nowadays in modern textbooks of electrodynamics (1.75-1.77). There are also several reviews on this topic (1.44,1.55,1.78-1.82). It starts from the equation for I, the radiated power per unit time interval of an electron moving on an arbitrary path $\vec{r}(t)$ with velocity momentum $\vec{p} = \gamma m\vec{v}$ and energy $E = \gamma mc^2$ (1.77).

$$I = \frac{2e^2}{3m^2c^3}\left[\left(\frac{d\vec{p}}{d\tau}\right)^2 - \frac{1}{c^2}\left(\frac{dE}{d\tau}\right)^2\right] \tag{1.1}$$

where e is the elektron charge, m its mass, c the velocity of light and $d\tau = dt/\gamma$ the element of proper time.

In specializing this in a fairly straightforward manner for a single electron moving with constant velocity c on a circular orbit (the second term in the square bracket vanishes) one obtains the power $I(\lambda,\psi)$ radiated off around the whole orbit in cgs units in erg/(sec·electron) into a wavelength interval $d\lambda$ and an interval $d\psi$ of the azimutal angle ψ (see Fig. 1.3):

$$I(\lambda,\psi) = \frac{27}{32\pi^3}\frac{e^2c}{R^3}\left(\frac{\lambda_c}{\lambda}\right)^4 \gamma^8 [1+(\gamma\psi)^2]^2 \left\{K_{2/3}^2(\xi) + \frac{(\gamma\psi)^2}{1+(\gamma\psi)^2}K_{1/3}^2(\xi)\right\}, \tag{1.2}$$

$$\text{with } \lambda_c = \frac{4\pi R}{3}\gamma^{-3} \text{ the "characteristic wavelength",} \tag{1.3}$$

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

$$\gamma = \frac{E}{mc^2},$$

with R the radius of curvature, $K_{1/3}$ and $K_{2/3}$ modified Besselfunctions of the second kind (1.83).

The two terms in the last large brackets of (1.2) are associated with the intensities in the two directions of polarization. $I_\parallel$ and $I_\perp$, the electric vector parallel and perpendicular to the plane of the orbit. If we define the linear degree of polarization P_L as usual we obtain

$$P_L = \frac{I_\parallel - I_\perp}{I_\parallel + I_\perp} = \frac{K_{2/3}^2(\xi) - \frac{(\gamma\psi)^2}{1+(\gamma\psi)^2}K_{1/3}^2(\xi)}{K_{2/3}^2(\xi) + \frac{(\gamma\psi)^2}{1+(\gamma\psi)^2}K_{1/3}^2(\xi)} \tag{1.4}$$

In Fig. 1.4 $I_\parallel$, $I_\perp$ and $P_\perp$ are plotted for a specific storage ring, DORIS (1.84). Since the two components of the electric vector have a well defined phase relation with respect to each other, namely $+\frac{\pi}{2}$ or $-\frac{\pi}{2}$ above or below the plane of the orbit respectively, one can also calculate a degree of circular polarization P_c, with the decomposition of the elliptically polarized wave into right and left hand waves with intensities I_R and I_L:

$$P_c = \frac{I_R - I_L}{I_R + I_L} = \pm \frac{\sqrt{I_\parallel I_\perp}}{I_\parallel + I_\perp} \qquad (1.5)$$

where the positive and negative signs correspond to $\psi > 0$ or $\psi < 0$ respectively.

Eq. (1.2) can be integrated over all azimutal angles ψ yielding the total power radiated by a single electron per second and unit wavelength interval.

$$I(\lambda) = \frac{3^{5/2}}{16\pi^2} \frac{e^2 c}{R^3} \gamma^7 \left(\frac{\lambda_c}{\lambda}\right)^3 \int_{\lambda_c/\lambda}^{\infty} d\eta \, K_{5/3}(\eta) \qquad (1.6)$$

where $K_{5/3}$ is another Bessel function of the second kind (1.83). Since (1.6) depends only on the ratio λ/λ_c and the machine parameters R and E this function can be obtained from a universal function $F(\frac{\lambda}{\lambda_c})$ with the appropriate prefactors. Appropriate functions of the type $F(\frac{\lambda}{\lambda_c})$ have been graphically displayed by several authors. Nowadays most of the SR centers have developed computer programs which allow for a rapid calculation of the intensities for different geometries.

When plotting (1.6) as a function of λ the intensity goes through a maximum value at $\lambda_m = 0.42\ \lambda_c$. Experiments have been performed at wavelengths as short as $1/4\ \lambda_m$. When looking at Fig. 1.5 one realizes that the intensity drops very rapidly below λ_c. It is also noted from this figure that other useful plots as

e.g. the number of photons per second and photon energy interval must not go through a maximum at all. Thus λ_m is a fairly arbitrary quantity.

For practical cases the power distribution in ψ can be of interest. In this case (1.2) can be integrated over all wavelengths yielding:

$$I(\psi) = \frac{e^2 c}{R^2} \gamma^5 \left[1 + (\gamma\psi)^2\right]^{-5/2} \left[\frac{7}{16} + \frac{5}{16} \frac{(\gamma\psi)^2}{1 + (\gamma\psi)^2}\right] \qquad (1.7)$$

On further integration finally yields the total power emitted by one single electron

$$I_{tot} = \frac{2}{3} \frac{e^2 c}{R^2} \gamma^4. \qquad (1.8)$$

All these intensities (1.2), (1.6), (1.7), and (1.8) can be transformed into intensities per unit current by multiplying the right hand sides by $2\pi R/(ec)$. Then the current has to be measured in electrostatic units. If the current is measured in Amp the above equations must be multiplied by $3 \cdot 10^9\ 2\pi R/(ec)$. In transforming the intensities per electron into intensities per unit current all those problems with actual machines which deviate from ideal circles due to the insertion of straight sections are eliminated. It is quite obvious that the only quantity which determines the observed intensity coming from the curved sections of a machine is the current which passes through these sections. For questions concerning the linear dependence of SR intensity with particle number see Sect. 1.2.2 below.

In the following we note in short a few useful expressions. Several more can be found in a report by CRLEN (1.85).

$$B(k\,gauss) \cdot R(m) = 33.35\ E(GeV) \qquad (1.9)$$

where B is the magnetic field.

$$\delta E(keV) = 88.5\, E^4(GeV)/R(m) \tag{1.10}$$

is the energy loss of one particle per turn.

$$\gamma = 1957\, E\,(GeV), \tag{1.11}$$

$$\lambda_c(\text{Å}) = 5.59\, R(m)/E^3(GeV) = 186.4/(B(kgauss)E^2(GeV)), \tag{1.12}$$

$$\epsilon_c(eV) = 2218\, E^3(GeV)/R(m) = 66.51\, B(kgauss)E^2(GeV), \tag{1.13}$$

with $\epsilon_c = hc/\lambda_c$, h = Planck's constant, $\epsilon_c(eV) = 12400/\lambda_c(\text{Å})$.

$$I(phot./(sec\cdot eV\cdot mrad) \approx 4.5\cdot 10^{12} R^{1/3}(m)\,\epsilon^{-2/3}(eV)\, j(mA) \tag{1.14}$$

for $\epsilon \ll \epsilon_c$,

where I is the intensity integrated over all angles ψ per horizontal angular intervall θ = 1 mrad (see Fig. 1.3) and j is the current.

The total power radiated is:

$$I(Watt) = 88.5\, E^4(GeV)\, j(mA)/R(m). \tag{1.15}$$

The angular spread $\Delta\psi$ (FWHM) of intensity can be approximated (1.77) as:

$$\begin{aligned} \Delta\psi &\approx \frac{2}{\gamma}\left(\frac{\epsilon_c}{\epsilon}\right)^{1/3} \quad \text{for } \epsilon \ll \epsilon_c \\ \Delta\psi &\approx \frac{2}{\gamma}\left(\frac{\epsilon_c}{3\epsilon}\right)^{1/2} \quad \text{for } \epsilon \gg \epsilon_c \end{aligned} \tag{1.16}$$

The luminosity $\eta(\psi,\epsilon)$ is defined as the number of photons per unit area of the source, A, (which is the cross section of the beam) and per unit solid angle.

In contrast to many classical sources $\eta(\psi,\epsilon)$ is a very anisotropic quantity. From (1.16) and (1.14) we obtain for $\epsilon \ll \epsilon_c$ as the maximum luminosity in the plane of the orbit:

$$\eta(0,\epsilon) \propto j\, R^{4/3} A^{-1} \epsilon^{-1/3}. \tag{1.17}$$

where A is the area of the source. This is plotted for a practical case in Fig. 1.6 together with $\Delta\psi$> which is not obtained from the approximations (1.16) but from an actual computer calculation (1.86, 1.87).

1.2.2 Considerations for real orbits

Coherence

In several equations of the previous section it is implicitly assumed that SR emission depends linearily on the number of electrons (the current). This holds only true as long as the positions of the electrons on the orbit are distributed statistically on the scale of the wavelength of light under consideration. Definitely no such correlation can be expected for optical and x-ray wavelengths. On the other hand at very long wavelengths which are much longer than the separation of the individual bunches of electrons in the machine there is no emission: a direct current does not emit radiation. This is a consequence of coherence. We further mention the very strong radiation at the wavelength which belongs to the regular separation of bunches on the orbit. This radiation is coherent with the particle current and can be quadratic in intensity with the number of electrons per bunch. Interactions with the microwave cavities and the vacuum pipe occurs through this emission (1.88). The radiation can lead to an indirect coupling of the oscillation of different bunches along the orbit. In this case one deals with storage ring machine physics. Only the thorough investigation of these processes can lead to a better understanding and mastering of storage rings with very high currents (see also Chapter 2). Theoretical treatments of the coherence problems can be found in several references (1.29 - 1.31).

Periodic wigglers

A special case of coherence is achieved with periodic wigglers also called undulators (1.89-1.93). The device generates a periodic deflection of a beam by small angles in a straight section of a storage ring (see Fig. 1.7). Up to one hundred wiggles are planned for such devices. The technical part is described in Chapter 2. In this case coherent emission of a single particle from the different equivalent points along its path is obtained. The coherence condition requires that the time difference for an electron and the light at the distance of two wiggle λ_o is equal to the period of the light wave. This leads to a peak in the spectrum at a wavelength

$$\lambda_p \approx \lambda_o / \gamma^2. \qquad (1.18)$$

The intensity at the peak position is proportional to n^2, where n is the number of wiggles. As for an example, we take E = 5 GeV, $\lambda_o = 10$ cm obtaining $\lambda_p \approx 10$ Å. Linear and helical wigglers have been proposed. Their emission differs with respect to the angular distribution and the polarization, predominantly linear and predominantly circular respectively (1.89). Emission for a linear wiggler in a synchrotron was recently measured successfully (1.93'). In this context stimulated emission within a wiggler is also discussed. After this effect was demonstrated (1.94-1.96) in the infrared, hopes have been raised for the production of a free electron x-ray laser (1.97). Most probably this goal is not achievable without the production of a high efficiency resonator which appears to be very difficult from present knowledge.

Synchrotron accelerators

Another modification of the equations in the previous section is needed to describe synchrotrons in which electrons are accelerated according to $\sin^2\omega_o t$, $\sin\omega_o t$ or other more complicated laws like e.g. in the so called "flat top" operation (1.98). Some of the necessary integrations can be carried out analytically (see e.g. (1.55)) but it is usually more convenient to do a numerical computer integration for actual cases.

Beam cross section and divergency

We now want to consider the modifications which are due to the actual cross section area and the divergency of the particle beam. Usually the linear beam dimensions are considerably less than 10 mm and the divergency in the vertical direction is less than one mrad. The particle dimensions σ_x, σ_y at any position of the orbit are obtained from the β-functions and the emittances ϵ ((1.85, 1.99, 1.100) as e.g. $\sigma_y = \sqrt{\epsilon\beta}$ (see Chapter 2). σ_y is one standard deviation of a gaussian distribution so that the full width at half maximum is given by

$$FWHM_y = 2.35\,\sigma_y = 2.35\sqrt{\epsilon\beta}. \qquad (1.19)$$

The angular divergency of the particle beam is usually negligible compared to the natural divergency of SR emission in the vacuum ultraviolet. It can be very important, however, in the x-ray region. The angular divergency is given by

$$FWHM_{y'} = 2.35\,\sigma_{y'} = 2.35\sqrt{\frac{\epsilon}{\beta}}\sqrt{1+\frac{\beta'^2}{4}}. \qquad (1.20)$$

Note the importance of the second square root factor which is due to the oblique orientation of the phase space ellipse (1.85). Usually the angular distribution of SR is approximated by a gaussian distribution and then the total angular width is obtained by quadratic addition (1.85, 1.101) (see also Fig. 3.7). As a consequence the maximum brightness as described by (1.17) and shown in Fig. 1.6 can be reduced in practical cases considerably in the x-ray regime especially for the highest energies. Further, the degree of linear polarization in the plane of the orbit and the degree of circular polarization above and below this plane are reduced. Thus, design goals for dedicated x-ray machines should rather aim at a reduction of beam divergency (with the exception of a few ports for special experiments) while the main goal for vacuum ultraviolet machines is a reduction of the beam size at all beam ports in order to increase the brightness.

It should be mentioned that (1.19) and (1.20) are calculated usually for a beam optics with an emittance which depends on the beam energy E like $\epsilon \propto E^2$. Electrostatic and electromagnetic interactions of the particles within the beam at higher currents will usually lead to an increase of ϵ with j (1.88, 1.101).

1.2.3 Time structure

Time structure is impregnated onto the light beam from different origins.:

1. In a snychrotron there is a natural repetition rate due to the acceleration cycle, e.g. 50 Hz at DESY. The electrons are accelerated usually for 10 msec from low energies up to a maximum energy of e.g. 7.5 GeV. Depending on the wavelength interval under inspection, radiation occurs during the last 2 - 7 msec. At the 10. msec electrons are extracted and a pause occurs till the 20. msec when the cycle is repeated.

2. In both synchrotrons and storage rings any structure in the charge distribution around the orbit is repeated with the frequency of revolution. This has e.g. at DESY and DORIS a periodicity of 1 μsec. In synchrotrons the bunch pockets are usually filled only for 3/4 of the circumference. Storage rings are frequently operated with only one bunch filled. In this case extremely short flashes (see below) are repeated at long intervals.

3. Only discrete stable positions occur around the orbit with a separation determined by the microwave frequency. If all these pockets are filled this leads to a pulse structure with 2 nsec intervals at DORIS. The pulse length is in the order of 200 psec.

Figure 1.8 gives a survey of the time structure of DORIS on all levels of time scale, even the very long term operational aspects are shown as accumulated

by KOSUCH (1.102). Time structure has several aspects for the experimentalist:

a) The duty cycle has consequences for dead time and count-loss considerations. It must be carefully considered when planning and evaluating an experiment.

b) Pulsed excitation of decaying processes like luminescence is a favourable tool for obtaining decay times. In addition transient phenomena can be observed with time resolution.

c) The luminosity of a SR source as shown in Fig. 1.6, is a time averaged luminosity. The peak luminosity during the pulse can be higher by three orders of magnitude. This property could be applied to the investigation of nonlinear processes and photon mixing.

1.3 Comparison with other sources

The final decision of an experimentalist to use SR instead of a conventional light source will usually be based on many aspects and involves all the details of an experiment. Intensity, nevertheless, in many cases is the dominant criterion and therefore we shall give detailed discussions here of this property of SR and other comparable light sources. Figure 1.6, showing the brightness, is a good starting point for such an analysis (1.85, 1.103). For actual experiments it is always necessary to remember that the differences in brightness come into play only if the acceptance a' of the experiment is matched to the emittance e' of the SR source. In many cases an experiment will at least in the vertical direction , accept more than what is emitted from a SR source. In this case the classical source gains by roughly a factor a'/e' if a' and e' are steric acceptance and emittance respectively. Although a SR source emits horizontally into 2π it is fairly difficult to extract more than 50 mrad from a magnet chamber in spite of mirror concepts (1.104) showing that this is principally possible. The intensity ratio of an experiment with SR compared to a classical source is therefore given by

$$\frac{I_{SR}}{I_{CL}} = \frac{\eta_{SR}}{\eta_{CL}} \cdot \frac{e'}{a'}, \qquad (1.21)$$

where η_{SR} and η_{CL} are the respective brightnesses.

1.3.1 Infrared and visible

The brightness of a very intense SR source, like DORIS, at a wavelength of 100 µm (0.01 eV) is by about two orders of magnitude higher than that of a high pressure mercury vapor lamp. The development of tunable lasers, however, has discouraged prospective users. On the other hand there are still gaps in the spectrum not covered by lasers and Fourier spectroscopy should be an appropriate technique. Two detailed papers are devoted to the infrared (1.105, 1.106). The visible and the near ultraviolet is covered by a sufficient number of other sources and therefore not of real interest for SR work. Nevertheless the pulsed time structure was used in the UV for an experiment to measure luminescence decays (1.107). This is quite simply achieved since SR in this region can be extracted through a window.

1.3.2 Vacuum ultraviolet

Table 1.3 gives a compilation of the most important continuum and resonance-line sources (1.108, 1.109). It is easily recognized that none of these sources covers a very large spectral range. The rare gas continuum sources, nevertheless, are fairly important. They give an intensity behind a monochromator which usually is by one order of magnitude less than that from a synchrotron and further reduced in comparison to a storage ring. The peak intensity for the He continuum at 800 Å was reported to be in the order of 10^9 Photons/(sec·Å) (1.109). There exist, however, some versions of these lamps which are optimized to a point that they can almost compete with a SR source at one point in the spectrum (1.110). Definitely the HeI resonance lamp used for photoemission experiments at 21.2 eV is superior to a SR source if it is used without a monochromator. In the order of $5\cdot10^{11}$ Photons/sec at the sample have been reported (1.111). This intensity might be achieved one day also with very favourably matched monochromators at dedicated storage rings. In This context also the recent development of excimer lasers in the energy region above 1000 Å has to be mentioned (1.111').

In summary SR definitely is superior to any other source in the vacuum ultraviolet if a source is needed which is tunable over a wide spectral range.

1.3.3 X-rays

As mentioned already before, the intensity of SR experiments in the x-ray region needs a more careful analysis than in the vacuum ultraviolet (1.86, 1.103, 1.112). In the x-ray region powerful x-ray generators exist (1.113') which consume up to 100 kW of power for rotating copper anodes and in the order of 5 kW for rotating aluminum anodes. As a rule of thumb 10^{-3} of the power is emitted as x-rays one half as the bremsstrahlen continuum and one half as characteristic lines. From Fig. 1.6 it is quite evident that the bremsstrahlen continuum cannot really compete with SR. Thus all the experiments which need tunability profit considerably from the very high intensity of SR. In addition, the good collimation makes simple plane crystal monochromators very efficient.

For experiments, which need only discrete wavelengths, a comparison with the characteristic x-ray lines is appropriate unless a well defined wavelength is needed which might not be available. If good collimation is necessary as with x-ray topography then again the high brightness of SR dominates. In cases, like photoelectric emission, monochromators can be constructed which accept 100 x 100 $mrad^2$. In this case the ratio a'/e' is $5\cdot10^3$ for a 10x0.2 $mrad^2$ emission and equal dimensions of the source. In this case other criteria may be involved when making a decision whether or not it might be worthwhile to use SR (see Sect. 3.6.2).

RABE (1.112) has given a detailed comparison not for the optimum case but for a more practical case which is summarized in Fig. 1.9. He compares SR from DESY with x-rays from a 45 kV, 50 mA (about 2.2 kW) x-ray tube. Advantage or disadvantage of SR depend very much on the angular acceptance of the experiments.

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Table 1.1 Synchrotrons used as light sources. E, particle energy; R, magnet radius; I, max. current (during the acceleration period); ε_c, characteristic photon energy; SR, synchrotron radiation.

Name	Location	E(GeV)	R(m)	I(mA)	ε_c(eV)	Remarks
Group I, ε_c = 1 - 60 eV						
PTB	Braunschweig	.14	.46		13	
SURF I	Washington	.24	.83	10	37	closed down
MOSCOW I	Moscow	.25			∿40	closed down
Group II, ε_c = 60 - 2000 eV						
GLASGOW	Glasgow	.33	1.25	.1	64	closed down
CORNELL I	Ithaca	.32	1		73	closed down
BONN I	Bonn	.5	1.7	30	163	SR Lab
C-60	Moscow	.68	2	10	349	SR Lab
CORNELL II	Ithaca	.7	1.5		508	closed down
FRASCATI	Frascati	1.1	3.6	15	821	closed down
LUSY	Lund	1.2	3.65	10	1050	SR station
INS-SOR I	Tokyo	1.3	4.0	60	1220	SR Lab
SIRIUS	Tomsk	1.3	4.2	20	1160	SR Lab
PACHRA	Moscow	1.3	4.0	100	1220	dedicated, SR Lab
Group III, ε_c = 2 - 30 keV						
BONN II	Bonn	2.5	7.65	30	4530	SR Lab
NINA	Daresbury	5.0	20.8	50	13,300	closed down
CEA	Cambridge/Mass.	6.0	26.0	30	18,400	closed down
ARUS	Yerevan	6.0	24.65	20	19,500	SR Lab
DESY	Hamburg	7.5	31.7	30	25,500	2 SR Labs
Group IV, $\varepsilon_c \geq$ 30 keV						
CORNELL III	Ithaca	12	120	2	32,000	closed down

Table 1.2 Storage rings (most of them 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.

Name	Location	E(GeV)	R(m)	I(mA)	ε_c(eV)	State
Group I, $\varepsilon_c \leq$ 60 eV						
TANTALUS I	Stoughton	.24	.64	100	48	dedicated
SURF II	Washington	.24	.83	30	37	dedicated
INS-SOR II	Tokyo	.30	1.1	200	54	dedicated
Group II, ε_c = 60 - 2000 eV						
ACO	Orsay	.55	1.11	100	333	dedicated
VEPP-2M	Novosibirsk	.67	∿2	∿100	∿350	SR Lab
BROOKHAVEN I	Upton	.70	∿2	1000	∿400	dedicated, plan. stage add. wigglers
ALADDIN	Stoughton	.75	2.08	1000	450	dedicated, plan. stage add. wigglers
BESSY	Berlin	.8	1.8	300	630	planning stage
SILVA	California	.8	∿1.8	300	630	proposed
ADONE	Frascati	1.5	5.0	60	1500	SR Lab
PAMPUS	Amsterdam	1.5	4.17	500	1800	dedicated, proposed add. wigglers
Group III, ε_c = 2 - 30 keV						
SRS (Nina II)	Daresbury	2.0	5.55	1000	3200	dedicated, add. wiggles under construction
BROOKHAVEN II	Upton	2.5	∿8.0	1000	4300	dedicated, plan. stage add. wigglers
DCI	Orsay	1.8	3.82	400	3390	SR Lab
MOSCOW	Moscow	2	5	1000	3500	dedicated, proposed
VEPP 3	Novosibirsk	2.2	6.15	80-500	3800	SR Lab, wiggler, under construction
PHOTON FACTORY	Japan	2.5	8.0	500	∿4300	dedicated, plan. stage
DORIS	Hamburg	5	12.12	100	22900	2 SR Labs
SPEAR	Stanford	4	12.7	60	11200	SR Labs
VEPP 4	Novosibirsk	6	33	100	14500	under constr., SR Labs
Group IV, $\varepsilon_c \geq$ 30 keV						
CESR	Ithaca	8	32	100	35000	under construction, SR Lab
PEP	Stanford	15	170	100	44000	under construction
PETRA	Hamburg	19	200	90	75000	under construction

Table 1.3 VUV and soft x-ray radiation sources. (From (1.108))

Source	Photon energy range (eV)	Linewidth	Remarks
He continuum	$12 \leq \hbar\omega \leq 21$	-	
Ne continuum	$12.4 \leq \hbar\omega \leq 16.8$	-	pressures of 50-200 torr
Ar continuum	$8 \leq \hbar\omega \leq 11.8$	-	
Kr continuum	$6.9 \leq \hbar\omega \leq 9.9$	-	
Xe continuum	$6.2 \leq \hbar\omega \leq 8.4$	-	
Hinteregger lamp	$4 \leq \hbar\omega \leq 14$	multiline	
He I resonance lamp	21.2	$\sim$1 meV ?	
He II resonance lamp	40.8	$\leq$10 meV	pressures of 0.1 - 0.5 torr
Ne I resonance lamp	16.8	$\sim$1 meV	
Ne II resonance lamp	26.9	<10 meV?	
BRV Source	$4 \leq \hbar\omega \leq 250$	continuum and multiline	10^{-4} torr
YM x-rays	132.3	0.5 eV	
ZrM x-rays	151.4	0.8 eV	
NbM x-rays	171.4	1.2 eV	
RhM x-rays	260.4	4.0 eV	
TiM x-rays	452	-	
MgK x-rays	1254	$\sim$0.7 eV	
Al K_α x-rays	1487	$\sim$0.8 eV	
Cu K_α x-rays	8055	$\sim$2.5 eV	

Figure Captions

Fig. 1.1 Nomenclature and basic facts about electromagnetic radiation from 1 - 10^5 eV.

Fig. 1.2 Growth of sources for SR since 1945. The circles drawn are approximately on scale.

Fig. 1.3 Geometry of SR emission. After (1.62)).

Fig. 1.4 Angular distribution of the two components $I_\parallel$ and $I_\perp$ (parallel and perpendicular to the orbit). Also the linear degree of polarization according to Eq. (1.4) and the circular degree of polarization according to Eq. (1.5) are given. (After (1.84)).

Fig. 1.5 Spectral distribution of intensity in an aperture 1 mrad wide and 1 mrad high centered at a tangential direction. The open circles indicate the characteristic energy ε_c according to Eq. (1.13). This aperture is well filled at low photon energies while only the part near the orbit is illuminated with hard x-rays. While 1 mrad horizontally is typically accepted by an experiment at a large storage ring, 10 mrad can easily be accepted at a small storage ring like e.g. TANTALUS I.

Fig. 1.6 Brightness of SR of DORIS (based on source size 1 x 10 mm^2) DESY (source size 3 x 10 mm^2), Cu K_α characteristic radiation and bremsstrahlung from a 60 kW x-ray tube (estimated from an effective source size of 1 x 1 mm^2), Al K_α characteristic radiation from a

5 kW x-ray tube (2 mm diameter spot size) and He I resonance line (1.111) (estimated source size 10 mm diameter, 20 meV line width and a guessed collimation of the 10^{12} emitted photons quoted into 0.01 sterad). Brightness of black-body radiation is also given. (From 1.86).

Fig. 1.7 Different types of wigglers: A wavelength shifter is just a sharp bend which serves to save energy in dedicated storage rings as SRS, BROOKHAVEN II, PHOTON FACTORY (see Table 1.2) by localizing the x-ray emission at a few points along the orbit. Multipole wigglers can be of planar or helical shape. Both serve to obtain high intensities in narrow spectral bands. (From [1.68].)

Fig. 1.8 Typical time structure of the SR emission from a storage ring (DORIS) at different expansions of the time scale. (From KOSUCH [1.102]).

Fig. 1.9 Quantitative comparison of the intensity of SR from DESY at different energies and of a typical Cu anode x-ray tube (45 keV, 50 mA) in different apertures. (From [1.112]).

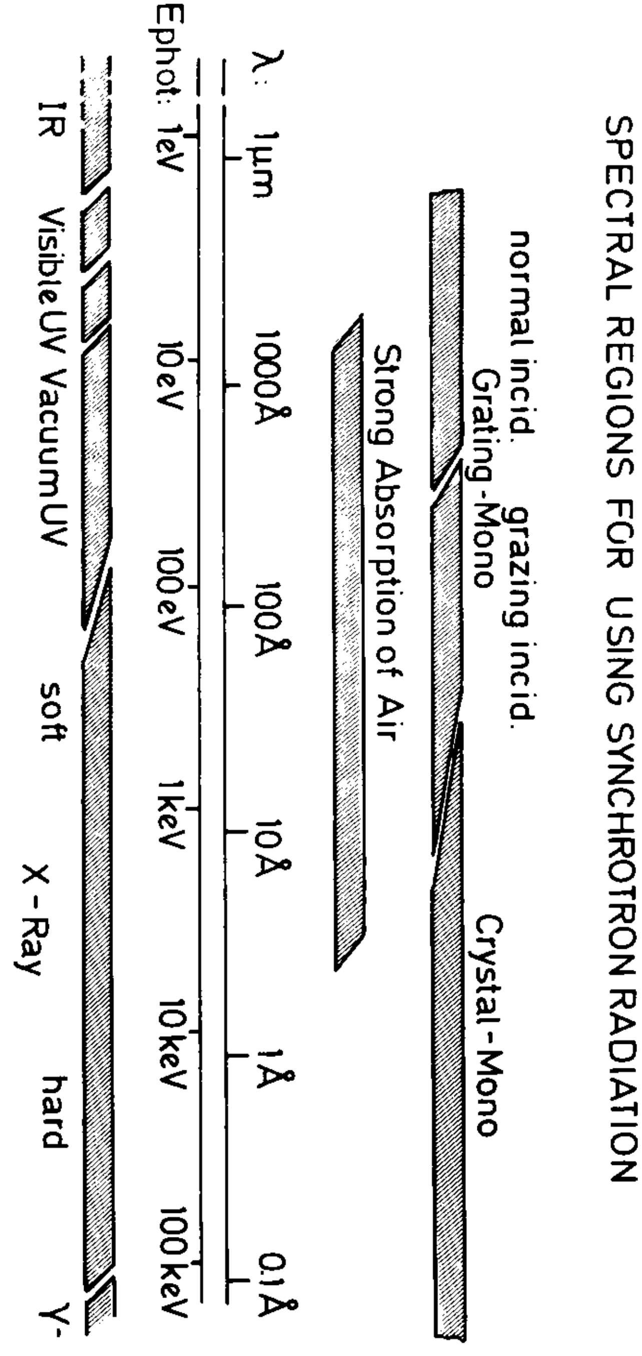


Fig. 1.1

DEVELOPMENT OF SYNCHROTRONS (SY) AND STORAGE RINGS (ST)
+APPROXIMATE START OF SR ACTIVITIES

< 0.1 GeV	GE BETATRON	1945		
	GE SYNCHROTRON	1946		
< 0.5 GeV	CORNELL I SY	1953	TANTALUS ST	1968
	MOSCOW I SY	1956	ACO ST	1973+
	NBS SY	1961	SURF II ST	1975
	BONN I SY	1962	INS-SOR ST	1976
	GLASGOW SY	1971+		
< 2 GeV	MOSCOW II SY	1961	VEPP 2M ST	1976
	CORNELL II SY	1961	DCI ST	1977
	FRASCATI SY	1962	ADONE ST	1978+
	TOKYO SY	1963	SRS ST	1979
	LUSY SY	1976+	ALADDIN ST	1980
			BROOKHAVEN I ST	1981
			BERLIN ST	1981
			PAMPUS ST	1982
< 8 GeV	CEA SY	1964	SPEAR ST	1973
	DESY SY	1964	DORIS ST	1974
	NINA SY	1966	VEPP 3 ST	1977
	BONN II SY	1968	VEPP 4 ST	1978
	ARUS SY	1970	BROOKHAVEN II ST	1981
			PHOTON FACTORY ST	1981
> 8 GeV			PETRA ST	1978
			PEP ST	1979
			CESR ST	1979

Fig. 1.2

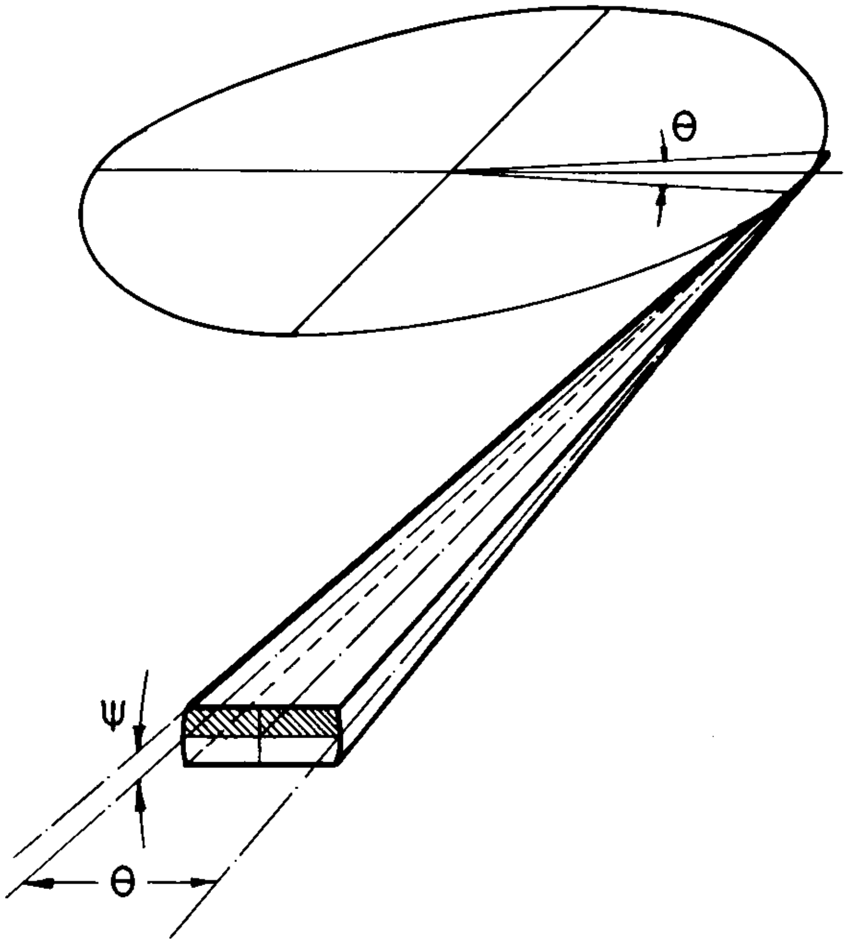
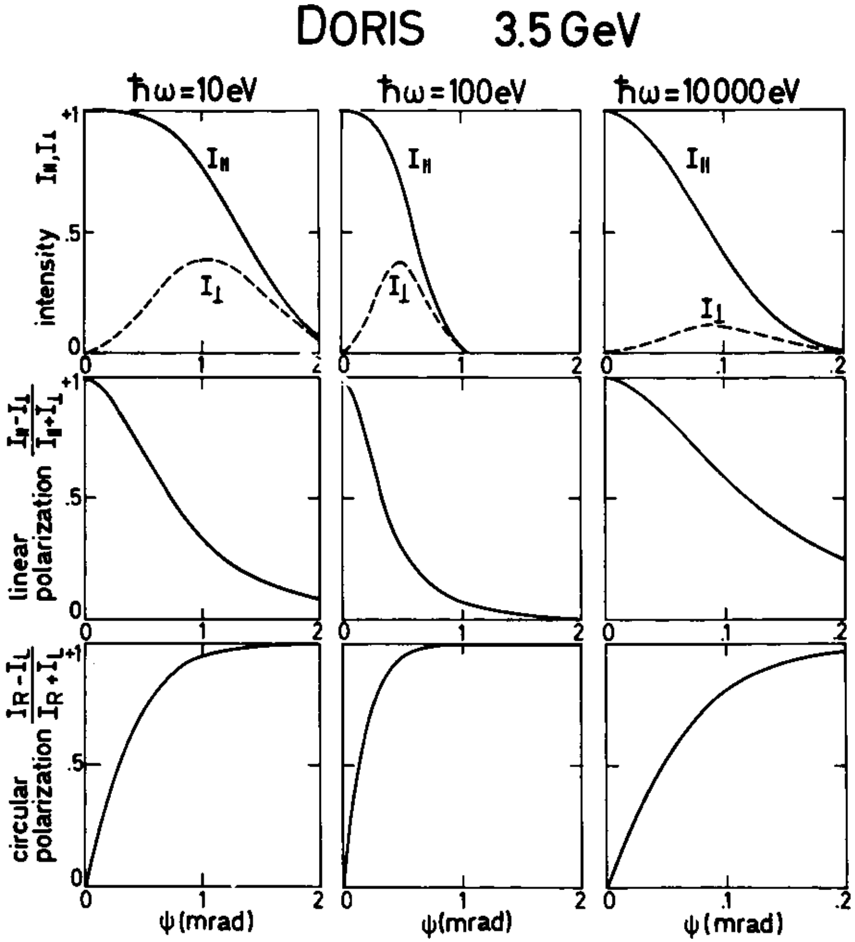
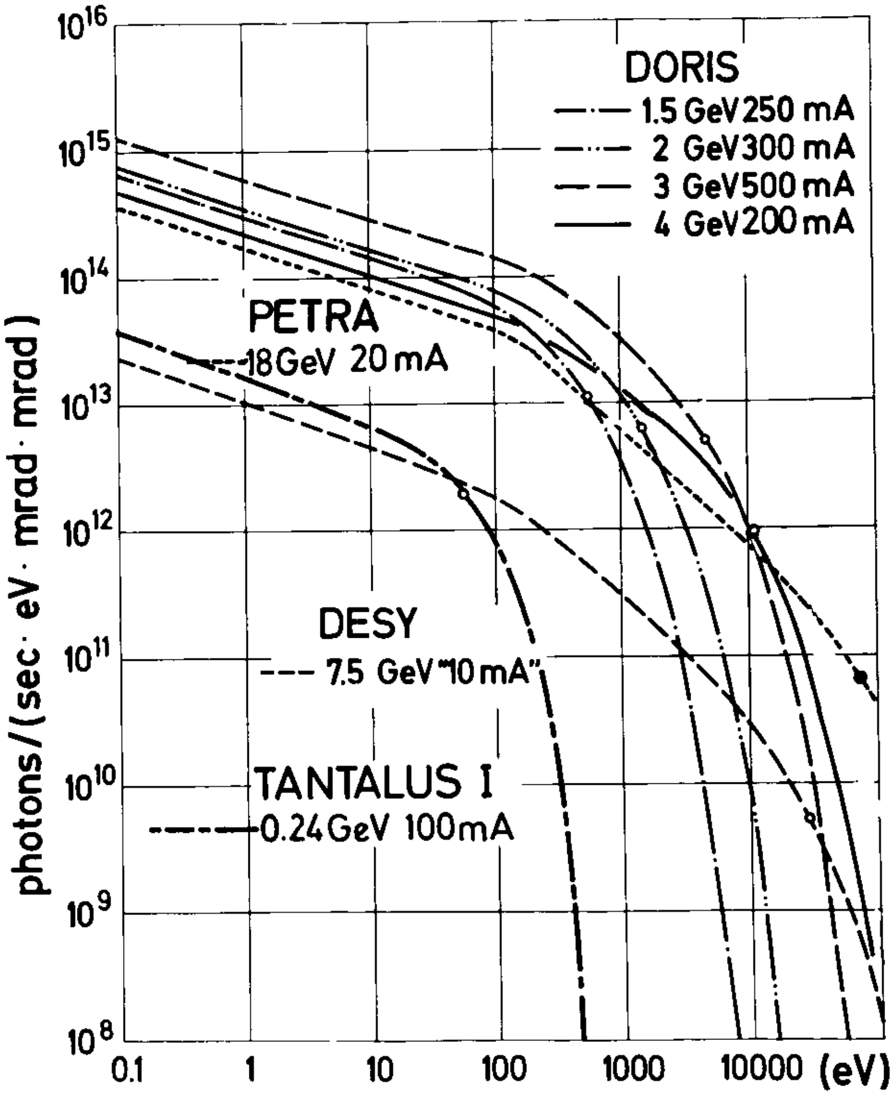


Fig. 1.3



DORIS 3.5 GeV
ħω=10eV
ħω=100eV
ħω=10000eV
intensity
linear polarization
circular polarization
ψ(mrad)
ψ(mrad)
ψ(mrad)

Fig. 1.4



DORIS
1.5 GeV 250 mA
2 GeV 300 mA
3 GeV 500 mA
4 GeV 200 mA
PETRA
18 GeV 20 mA
DESY
7.5 GeV "10 mA"
TANTALUS I
0.24 GeV 100 mA
photons/(sec · eV · mrad · mrad)
0.1
1
10
100
1000
10000
(eV)

Fig. 1.5

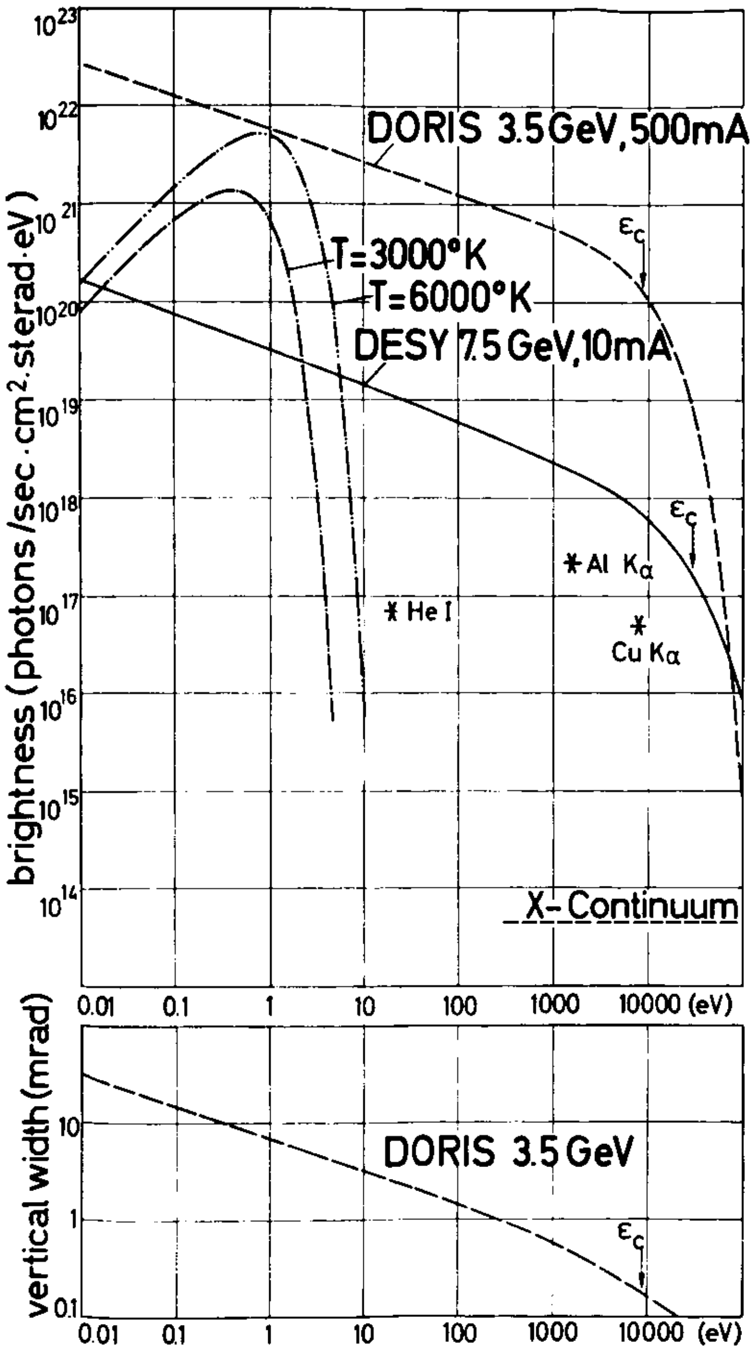

DORIS 3.5 GeV, 500mA
T=3000°K
T=6000°K
DESY 7.5 GeV, 10mA
ε_c
* Al K_α
* He I
* Cu K_α
X-Continuum
brightness (photons/sec · cm^2 · sterad · eV)
vertical width (mrad)
DORIS 3.5 GeV
0.01 0.1 1 10 100 1000 10000 (eV)

Fig. 1.6

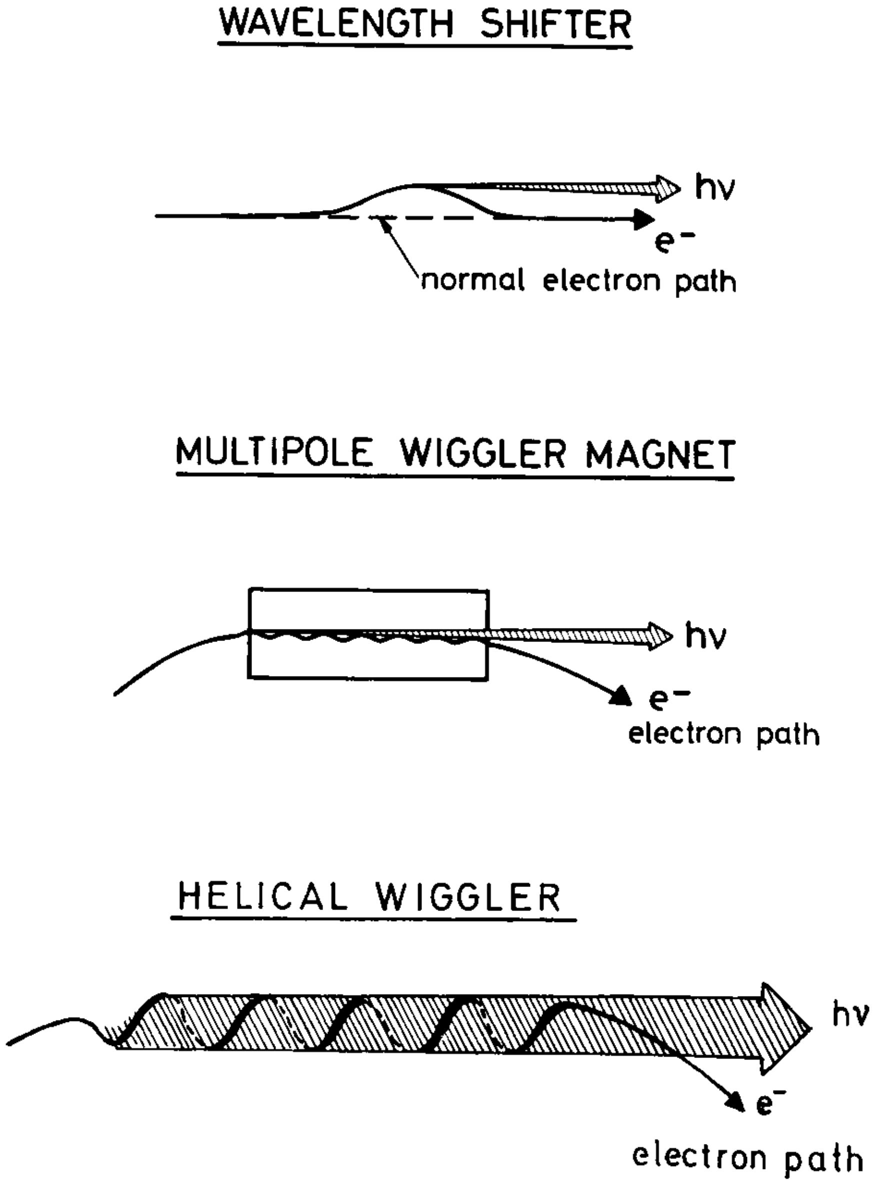
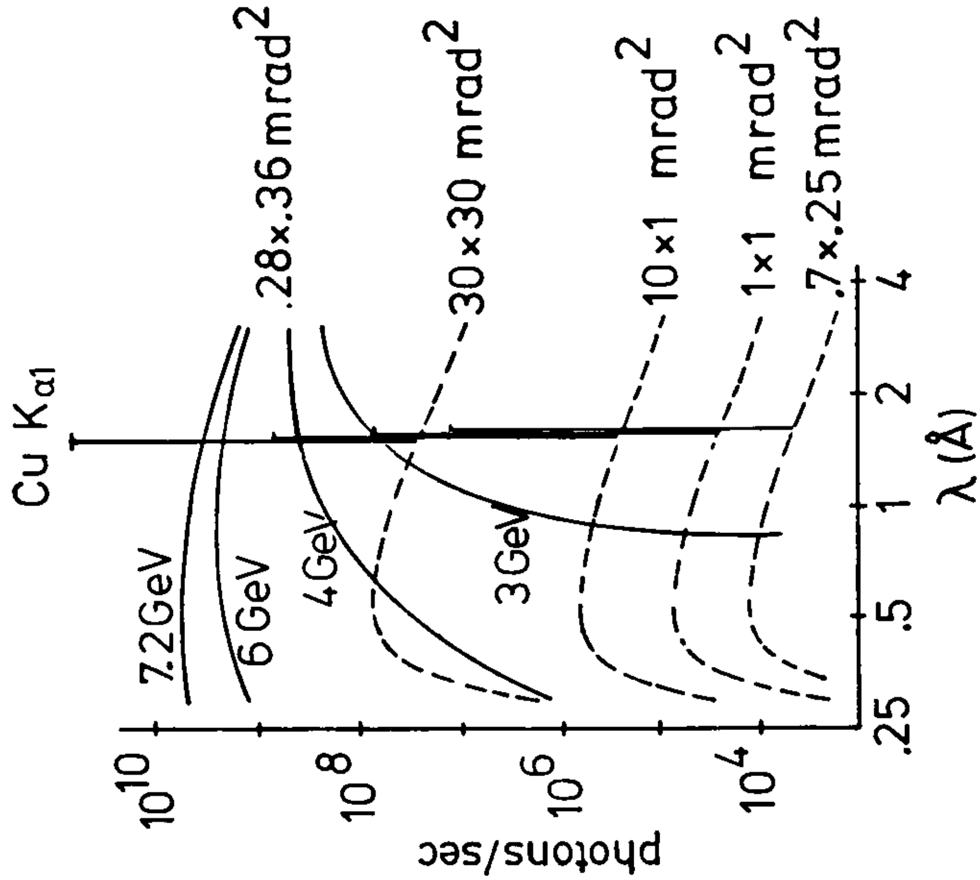
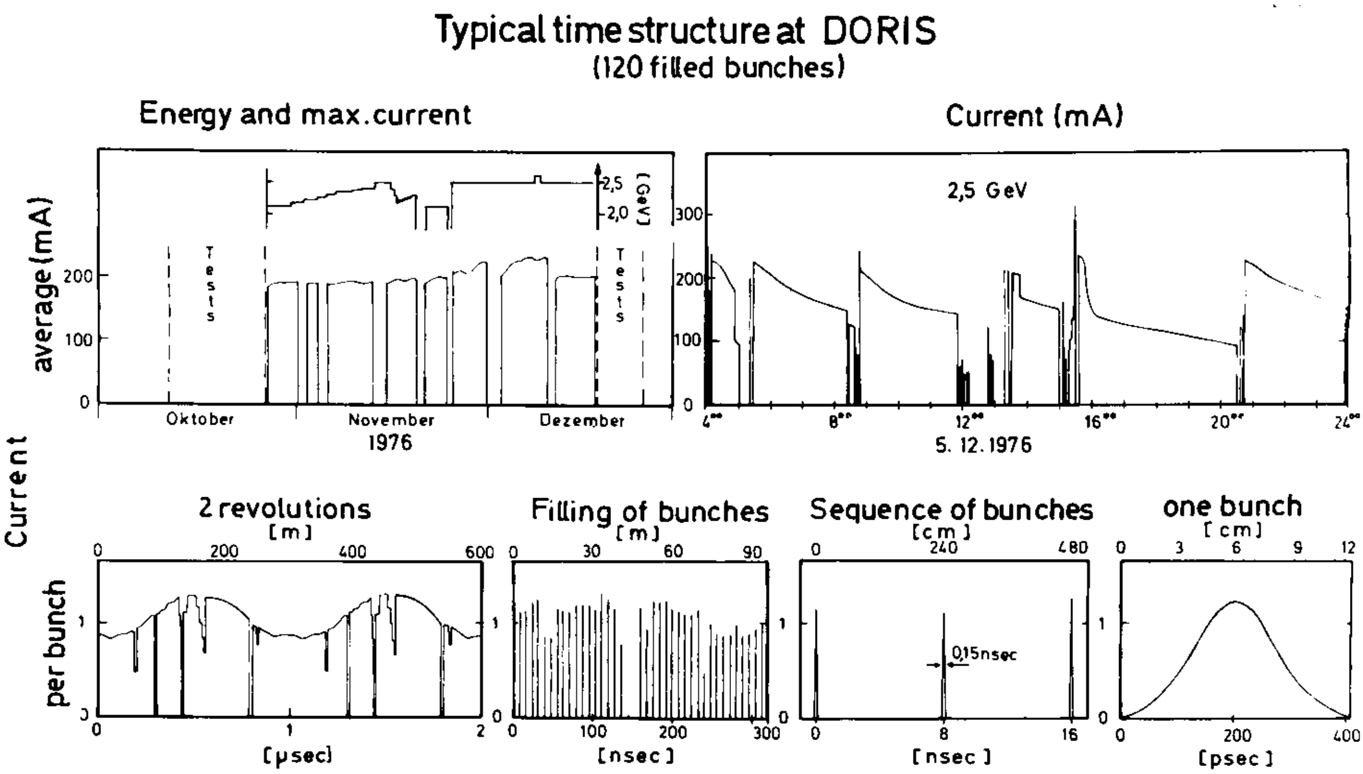

WAVELENGTH SHIFTER
hν
e⁻
normal electron path
MULTIPOLE WIGGLER MAGNET
hν
e⁻
electron path
HELICAL WIGGLER
hν
e⁻
electron path

Fig. 1.7



Cu Kα1
7.2GeV
6GeV
4GeV
3GeV
.28x.36 mrad²
30x30 mrad²
10x1 mrad²
1x1 mrad²
7x.25 mrad²
photons/sec
λ (Å)

Fig. 1.9



Typical time structure at DORIS
(120 filled bunches)
Energy and max. current
Current (mA)
average (mA)
Tests
Oktober
November
Dezember
1976
2,5 GeV
5. 12. 1976
Current per bunch
2 revolutions
Filling of bunches
Sequence of bunches
one bunch
[μsec]
[nsec]
[psec]
0,15nsec

Fig. 1.8