International Tables for Crystallography (2006). Vol. C, Section 4.2.1.5, pp. 196–198.

Table 4.2.1.4. *Relative permissible loading for different target materials*

Cu	Cr	Fe	Co	Mo	Ag	W
1.0	0.9	0.6	0.9	1.2	1.0	1.2

from some shell other than the *K* shell is very small and most of the photons emitted are *K* photons. The number of photons emitted into a solid angle of 4π, uncorrected for absorption, is given by the strength of the source in Curies (1 Curie = 3.7×10^{10} disintegrations s^{-1}), since each disintegration produces one photon. A list of these nuclei (after Dyson, 1973) is given in Table 4.2.1.5.

Useful radioactive sources are also made by mixing a pure β-emitter with a target material. These sources produce a continuous spectrum in addition to the characteristic line spectrum. The nuclide most commonly used for this purpose is tritium which emits β particles with an energy up to 18 keV and which has a half-life of 12.4 a.

Radioactive X-ray sources have been reviewed by Dyson (1973).

4.2.1.5. *Synchrotron-radiation sources*

The growing importance of synchrotron radiation is attested by a large number of monographs (Kunz, 1979; Winick, 1980; Stuhrmann, 1982; Koch, 1983) and review articles (Godwin, 1968; Kulipanov & Strinskii, 1977; Lea, 1978; Winick & Bienenstock, 1978; Helliwell, 1984; Buras, 1985). Project studies for storage rings such as the European Synchrotron Radiation Facility, the ESRF (Farge & Duke, 1979; Thompson & Poole, 1979; Buras & Marr, 1979; Buras & Tazzari, 1984) are still worth consulting for the reasoning that lay behind the design; the ESRF has, in fact, achieved or even exceeded the design parameters (Laclare, 1994).

A charged particle with energy *E* and mass *m* moving in a circular orbit of radius *R* at a constant speed *v* radiates a power *P* into a solid angle of 4π, where

$$P = 2e^2c(v/c)^4(E/mc^2)^4/3R^2. \qquad (4.2.1.17)$$

The orbit of the particle can be maintained only if the energy lost in the form of electromagnetic radiation is constantly replenished. In an electron synchrotron or in a storage ring, the circulating particles are electrons or positrons maintained in a closed orbit by a magnetic field; their energy is supplied or restored by means of an oscillating radio-frequency (RF) electric field at one or more places in the orbit. In a synchrotron, designed for nuclear-physics experiments, the circulating particles are injected from a linear accelerator, accelerated up to full energy by the RF field and then deflected into a target with a cycle frequency of about 50 Hz. The synchrotron radiation is thus produced in the form of pulses of this frequency. A storage ring, on the other hand, is filled with electrons or positrons and after acceleration the particle energy is maintained by the RF field; the current ideally circulates for many hours and decays only as a result of collisions with remaining gas molecules. At present, only storage rings are used as sources of synchrotron radiation and many of these are dedicated entirely to the production of radiation: they are not used at all, or are used only for limited periods, for nuclear-physics collision experiments.

In equation (4.2.1.17), we may substitute for the various constants and obtain for the radiated power

Table 4.2.1.5. *Radionuclides decaying wholly by electron capture, and yielding little or no γ-radiation*

Nuclide	Half-life	X-rays		Remarks
		Element	$K\alpha_1$ (keV)	
^{37}Ar	35 d	Cl	2.622	–
^{51}Cr	27.8 d	V	4.952	γ at 320 keV
^{55}Fe	2.6 a	Mn	5.898	–
^{71}Ge	11.4 d	Ga	9.251	–
^{103}Pd	17 d	Rh	20.214	Several γ's; all weak
^{109}Cd	453 d	Ag	22.16	γ at 88 keV
^{125}I	60 d	Te	27.47	γ at 35.4 keV
^{131}Cs	10 d	Xe	29.80	–
^{145}Pm	17.7a	Nd	37.36	γ's at 67 and 72 keV
^{145}Sm	340 d	Pm	38.65	γ's at 61 keV; weak γ at 485 keV
^{179}Ta	600 d	Hf	55.76	–
^{181}W	140 d	Ta	57.52	γ at 6.5 keV; weak γ's at 136, 153 keV
^{205}Pb	5×10^7a	Tl	*L* only (L_{α_1} = 10.27 keV)	–

$$P = 0.0885\,E^4I/R, \qquad (4.2.1.18)$$

where *E* is in GeV (10^9 eV), *I* is the circulating electron or positron current in milliamperes, and *R* is in metres. Thus, for example, at the Daresbury storage ring in England, $R = 5.5$ m and, for operation at 2 GeV and 200 mA, $P = 51.5$ kW. Storage rings with a total power of the order of 1 MW are planned.

For relativistic electrons, the electromagnetic radiation is compressed into a fan-shaped beam tangential to the orbit with a vertical opening angle $\psi \simeq mc^2/E$, *i.e.* ~ 0.25 mrad for $E = 2$ GeV (Fig. 4.2.1.5). This fan rotates with circulating electrons: if the ring is filled with *n* bunches of electrons, a stationary observer will see *n* flashes of radiation every $2\pi R/c$ s, the duration of each flash being less than 1 ns.

The spectral distribution of synchrotron radiation extends from the infrared to the X-ray region; Schwinger (1949) gives the instantaneous power radiated by a monoenergetic electron in a circular motion per unit wavelength interval as a function of wavelength (Winick, 1980). An important parameter specifying the distribution is the critical wavelength λ_c: half the total power radiated, but only $\sim 9\%$ of the total number of photons, is at $\lambda < \lambda_c$ (Fig. 4.2.1.6). λ_c is given by

$$\lambda_c = 4\pi R/3(E/mc^2)^3, \qquad (4.2.1.19)$$

from which it follows that λ_c in Å can be expressed as

$$\lambda_c = 18.64/(BE^2), \qquad (4.2.1.20)$$

where B $(= 3.34\,E/R)$ is the magnetic bending field in T, *E* is in GeV, and *R* is in metres.

Synchrotron radiation is highly polarized. In an ideal ring where all electrons are parallel to one another in a central orbit, the radiation in the orbital plane is linearly polarized with the electric vector lying in this plane. Outside the plane, the radiation is elliptically polarized.

In practice, the electron path in a storage ring is not a circle. The 'ring' consists of an alternation of straight sections and bending magnets and beam lines are installed at these magnets.

So-called *insertion devices* with a zero magnetic field integral, *i.e. wigglers* and *undulators*, may be inserted in the straight sections (Fig. 4.2.1.7). A wiggler consists of one or more dipole magnets with alternating magnetic field directions aligned transverse to the orbit. The critical wavelength can thus be shifted towards shorter values because the bending radius can be made small over a short section, especially when superconducting magnets are used. Such a device is called a *wavelength shifter*. If it has N dipoles, the radiation from the different poles is added to give an N-fold increase in intensity. Wigglers can be horizontal or vertical.

In a wiggler, the maximum divergence 2α of the electron beam is much larger than ψ, the vertical aperture of the radiation cone in the spectral region of interest (Fig. 4.2.1.5). If $2\alpha \ll \psi$ and if, in addition, the magnet poles of a multipole device have a short period λ_0, the device becomes an undulator: interference will take place between the radiation emitted at two points λ_0 apart on the electron trajectory (Fig. 4.2.1.8). The spectrum at an angle φ to the axis observed through a pin-hole will consist of a single spectral line and its harmonics of wavelengths

$$\lambda_i = i^{-1}\lambda_0[(E/mc^2)^{-2} + \alpha^2/2 + \theta^2]/2 \quad (4.2.1.21)$$

(Hofmann, 1978). Typically, the bandwidth of the lines, $\delta\lambda/\lambda$, will be ~ 0.01 to 0.1 and the photon flux per unit band width from the undulator will be many orders of magnitude greater than that from a bending magnet. Existing undulators have been designed for photon energies below 2 keV; higher energies, because of the relatively weak magnetic fields necessitated by the need to keep λ_0 small [equation (4.2.1.21)], require a high electron energy: undulators with a fundamental wavelength in the neighbourhood of 0.86 Å are planned for the European storage ring (Buras & Tazzari, 1984).

The wavelength spectra for a bending magnet, a wiggler and an undulator for the ESRF, are shown in Fig. 4.2.1.9. A comparison of the spectra from an existing storage ring with the spectrum of a rotating-anode tube is shown in Fig. 4.2.1.10.

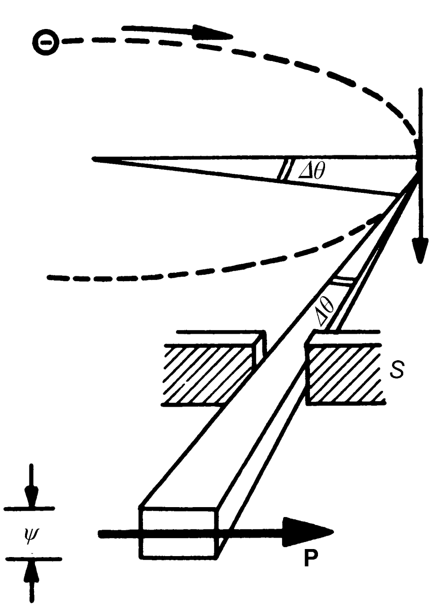

Fig. 4.2.1.5. Synchrotron radiation emitted by a relativistic electron travelling in a curved trajectory. B is the magnetic field perpendicular to the plane of the electron orbit; ψ is the natural opening angle in the vertical plane; P is the direction of polarization. The slit S defines the length of the arc of angle $\Delta\theta$ from which the radiation is taken. From Buras & Tazzari (1984); courtesy of ESRP.

The important properties of synchrotron-radiation sources are:
(1) high intensity;
(2) very broad continuous spectral range;
(3) narrow angular collimation;
(4) small source size;
(5) high degree of polarization;
(6) regularly pulsed time structure;
(7) computability of properties.

Table 4.2.1.6 (after Buras & Tazzari, 1984) compares the most important parameters of the European Synchrotron Radiation Facility (ESRF) with a number of other storage rings. In this table, BM and W signify bending-magnet and wiggler beam lines, respectively, σ_x and σ_z' is the source divergence; the flux is integrated in the vertical plane. The ESRF is seen to have a higher flux than other sources; even more impressive by virtue of the small dimensions of the source size and divergence are its improvements in spectral brightness (defined as the number of photons s^{-1} per unit solid angle per 0.1% bandwidth) and in spectral brilliance (defined as the number of photons s^{-1} per unit solid angle per unit area of the source per 0.1% bandwidth). In comparing different synchrotron-radiation sources with one another and with conventional sources (Fig. 4.2.1.10), the relative quantity for comparison may be flux, brightness or brilliance, depending on the type of diffraction experiment and the type of collimation adopted. Table 4.2.1.7 (due to Farge & Duke, 1979) attempts to compare intensity factors for a number of typical experiments. In general, a high brightness is important in experiments that do not embody focusing elements, such as mirrors or

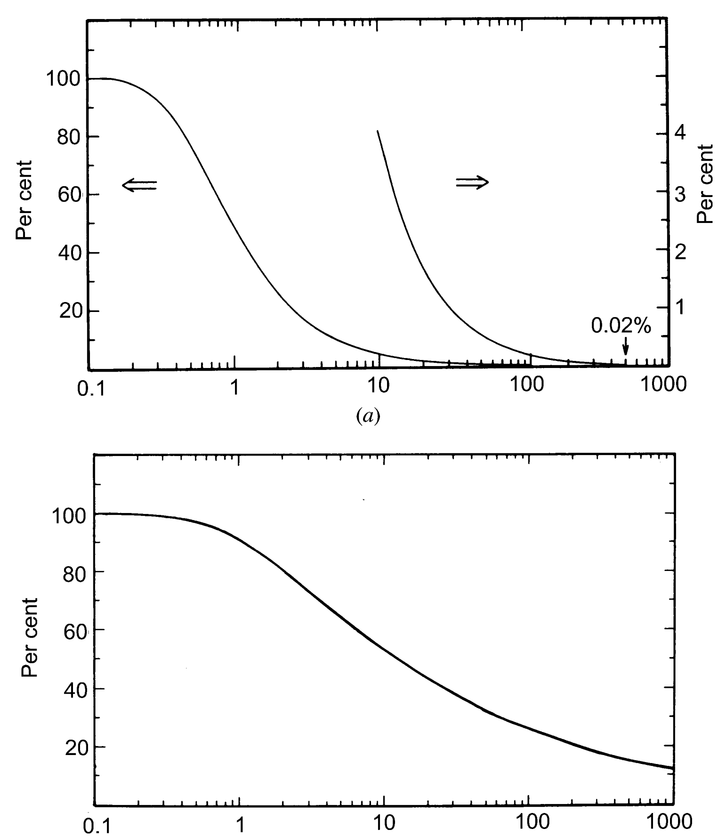

Fig. 4.2.1.6. Synchrotron-radiation spectrum: percentage per unit wavelength interval (a) of power of total power and (b) of number of photons of total number of photons at wavelengths greater than λ *versus* λ/λ_c. Note that half the power but only 9% of the photons are radiated at wavelengths less than λ_c; courtesy of H. Winick.

curved crystals, and a high brilliance in those experiments that do.

Many surveys of existing and planned synchrotron-radiation sources have been published since the compilation of Table 4.2.1.6. Figure 4.2.1.11, taken from a recent review (Suller, 1992), is a graphical illustration of the growth and the distribution of these sources. An earlier census is due to Huke & Kobayakawa (1989). Many detailed descriptions of beam lines for particular purposes, such as protein crystallography (*e.g* Fourme, 1992) or at individual storage rings (*e.g.* Kusev, Raiko & Skuratowski, 1992) have appeared: these are too numerous to list here and can be located by reference to *Synchrotron Radiation News*.

4.2.1.6. *Plasma X-ray sources*

Plasma sources of hard X-rays are being investigated in many laboratories. Most of the material in this section is derived from publications from the Laboratory for Laser Energetics, University of Rochester, USA. Plasma sources of very soft X-rays have been reviewed by Byer, Kuhn, Reed & Trail (1983).

The peak wavelength of emission from a black-body radiator falls into the ultraviolet at about 10^5 K and into the X-ray region between 10^6 and 10^7 K. At these temperatures, matter is in the form of a plasma that consists of highly ionized atoms and of electrons with energies of several keV. The only successful methods of heating plasmas to temperatures in excess of 10^6 K is by means of high-energy laser beams with intensities of 10^{12} W mm^{-2} or more. The duration of the laser pulse must be less than 1 ns so that the plasma cannot flow away from the pulse. When the plasmas are created from elements with $15 < Z < 25$, they consist mainly of ions stripped to the K shell, that is of hydrogen- and helium-like ions. The X-ray spectrum (Fig. 4.2.1.12) then contains a main group of lines with a bandwidth for the group of about 1%; the band is situated slightly below the K-absorption edge of the target material. The intensity of the band drops with increasing atomic number. For diffraction studies, Forsyth & Frankel (1980, 1984) and Frankel & Forsyth (1979, 1985) used a multi-stage Nd^{3+}:glass laser (Seka, Soures, Lewis, Bunkenburg, Brown, Jacobs, Mourou & Zimmermann, 1980), which was able to deliver up to 220 J per pulse of width 700 ps. They obtained 6×10^{14} photons pulse^{-1} for a Cl^{15+} plasma with a mean wavelength of about 4.45 Å and about 3×10^{13} photons pulse^{-1} for a Fe^{24+} plasma at about 1.87 Å (Yaakobi, Bourke, Conturie, Delettrez, Forsyth, Frankel, Goldman, McCrory, Seka, Soures, Burek & Deslattes, 1981). More recently, the laser was fitted

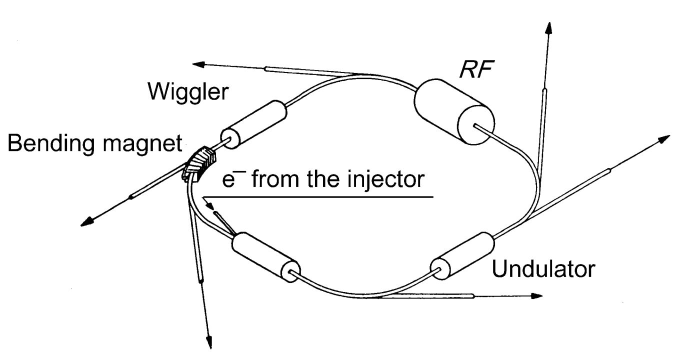

Fig. 4.2.1.7. Main components of a dedicated electron storage-ring synchrotron-radiation source. For clarity, only one bending magnet is shown. From Buras & Tazzari (1984); courtesy of ESRP.

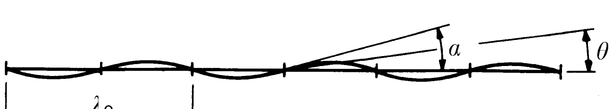

Fig. 4.2.1.8. Electron trajectory within a multipole wiggler or undulator. λ_0 is the spatial period, α the maximum deflection angle, and θ the observation angle. From Buras & Tazzari (1984); courtesy of ESRP.

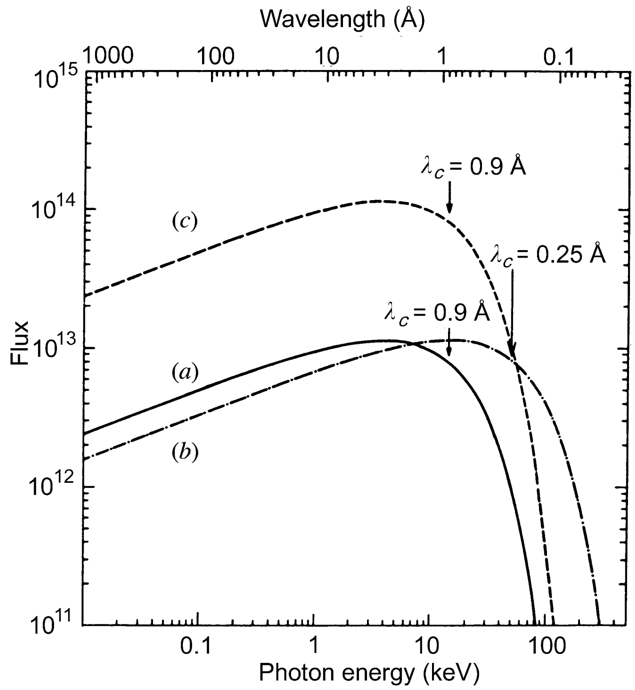

Fig. 4.2.1.9. Spectral distribution and critical wavelengths for (*a*) a dipole magnet, (*b*) a wavelength shifter, and (*c*) a multipole wiggler for the proposed ESRF. From Buras & Tazzari (1984); courtesy of ESRP.

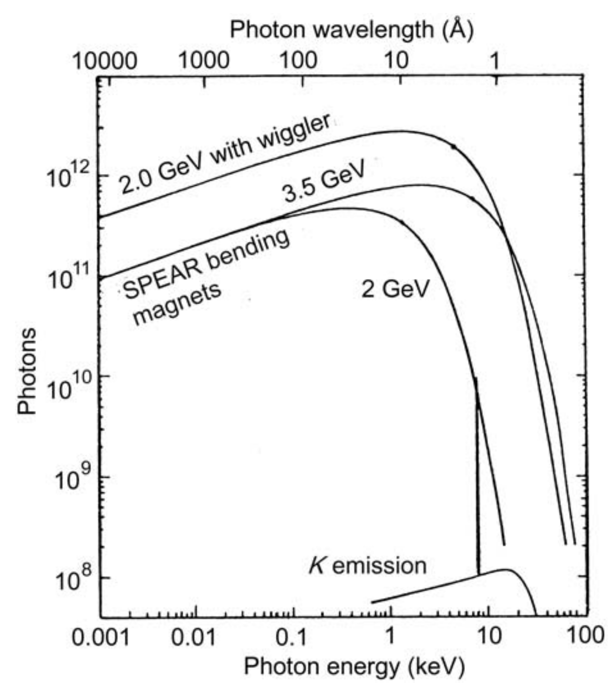

Fig. 4.2.1.10. Comparison of the spectra from the storage ring SPEAR in photons s^{-1} mA^{-1} mrad^{-1} per 1% passband (1978 performance) and a rotating-anode X-ray generator. From Nagel (1980); courtesy of K. O. Hodgson.