International Tables for Crystallography (2006). Vol. C, Section 4.2.1.4, pp. 195–196.

manufactured by Enraf, Rigaku-Denki, and Siemens, these lifetimes are about the same as the lifetime of the filament under good vacuum conditions, that is, of the order of 1000 h.

Phillips (1985) has written a review article on stationary and rotating-anode X-ray tubes that contains many important practical details.

4.2.1.3.1. *Power dissipation in the anode*

The allowable power loading of X-ray tube targets is determined by the temperature of the target surface, which must remain below the melting point. Müller (1927, 1929, 1931) first calculated the maximum loading both for stationary and for rotating anodes. His calculations were refined by Oosterkamp (1948) who considered, in particular, targets of finite thickness, and who also treated pulsed operation of the tube. For normal conditions, Oosterkamp's conclusions and those of Ishimura, Shiraiwa & Sawada (1957) do not greatly differ from those of Müller, which are in adequate agreement with experimental observations.

For an elliptical focal spot with axes f_1 and f_2, Müller's formula for the maximum power dissipation on a stationary anode, assumed to be a water-cooled block of dimensions large compared with the focal-spot dimensions, can be written

$$W_{\rm stat} = 2.063(T_M - T_0)Kf_1\mu(f_1,f_2), \qquad (4.2.1.12)$$

where K is the specific thermal conductivity of the target material in W mm^{-1}, T_M is the maximum temperature at the centre of the focal spot on the target, that is, a temperature well below the melting point of the target material, and T_0 is the temperature of the cold surface of the target, that is, of the cooling water. The function μ is shown in Fig. 4.2.1.4. For copper, K is 400 W m^{-1} and, with $T_M - T_0 = 500$ K,

$$W_{\rm stat} = 425\mu f_1. \qquad (4.2.1.13)$$

For $f_2/f_1 = 0.1$, and $\mu = 0.425$, this equation becomes

$$W_{\rm stat} = 180f_1. \qquad (4.2.1.14)$$

In these last two equations, f_1 is in mm.

For a rotating target, Müller found that the permissible power dissipation was given by

$$W_{\rm rot} = 1.428\,K(T_M - T_0)f_1(f_2\rho Cv/2K)^{1/2}, \qquad (4.2.1.15)$$

where f_2 is the short dimension of the focus, assumed to be in the direction of motion of the target, v is the linear velocity, ρ is the density of the target material, and C is its specific heat.

For a copper target with f_1 and f_2 in mm and v in mm s^{-1},

$$W_{\rm rot} = 26.4f_1(f_2v)^{1/2}. \qquad (4.2.1.16)$$

Equation (4.2.1.16) shows that for very narrow focal spots rotating-anode tubes give useful improvements in permissible loading only if the surface speed is very high (see Table 4.2.1.3). The reason is that with large foci on stationary anodes the isothermal surfaces in the target are planar; with fine foci, these surfaces become cylindrical and this already makes for very efficient cooling without the need for rotation. Rotating anodes are thus most useful for medium-size foci (200 to 500 μm) since for the larger focal spots it becomes very expensive to construct power supplies capable of supplying the permissible amount of power.

Table 4.2.1.3 shows the recommended loading for a number of commercially available X-ray tubes with copper targets, which will be seen to be in qualitative agreement with the calculations. Some of the discrepancy is due to the fact that the value of $K(T_M - T_0)$ for the copper–chromium alloy targets used in actual X-ray tubes is appreciably lower than the value for pure copper used here. To a good approximation, the permissible loading for other targets can be derived by multiplying those in Table 4.2.1.3 by the factors shown in Table 4.2.1.4. It is worth noting that the recommended loading of commercial stationary-target X-ray tubes has increased steadily in recent years. This is largely due to improvements in the water cooling of the back surface of the target by increasing the turbulence of the water and the effective surface area of the cooled surface.

In considering Table 4.2.1.3, it should be noted that the linear velocities of the highest-power X-ray-tube anode have already reached a speed that Yoshimatsu & Kozaki (1977) consider the practical limit, which is set by the mechanical properties of engineering materials. It should also be noted that much higher specific loads can be achieved for true micro-focus tubes, *e.g.* 50 kW mm^{-2} for a 25 μm Ehrenberg & Spear tube and 1000 kW mm^{-2} for a tube with a 1 μm focus (Goldsztaub, 1947; Cosslett & Nixon, 1951, 1960).

Some tubes with focus spots of less than 10 μm utilize foil or needle targets. These targets and the heat dissipated in them have been discussed by Cosslett & Nixon (1960). The dissipation is less than that in a massive target by a factor of about 3 for a foil and 10 for a needle, but, in view of the low absolute power, target movement and even water-cooling can be dispensed with.

4.2.1.4. *Radioactive X-ray sources*

Radioactive sources of X-rays are mainly of interest to crystallographers for the calibration of X-ray detectors where they have the great advantage of being completely stable with time, or at least of having an accurately known decay rate. For some purposes, spectral purity of the radiation is important; radionuclides that decay wholly by electron capture are particularly useful as they produce little or no β or other radiation. In this type of decay, the atomic number of the daughter nucleus is one less than that of the decaying isotope, and the emitted X-rays are characteristic of the daughter nucleus. In some cases, the probability of electron capture taking place

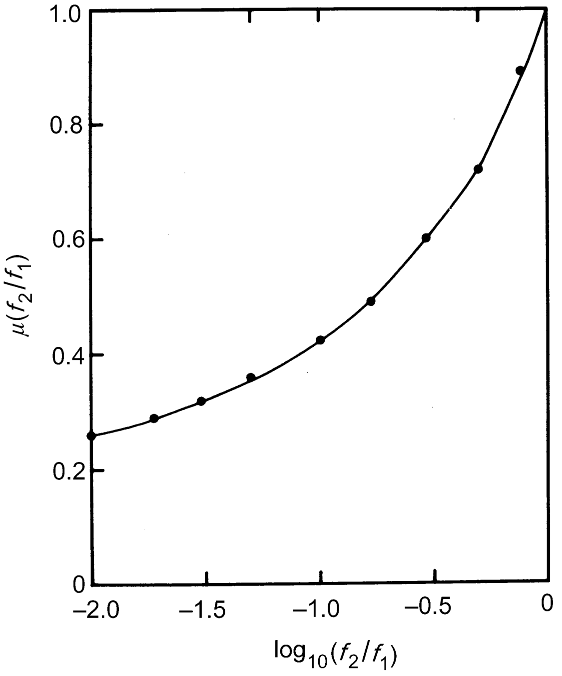

Fig. 4.2.1.4. The function μ in Müller's equation (equation 4.2.1.12) as a function of the ratio of width to length of the focal spot.

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.