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is necessary to employ an electron lens (which may be magnetic or electrostatic) to produce on the target a demagnified image of the electron cross-over, which is close to the grid of the tube cathode.

The maximum power that can be dissipated in the target without damaging the surface has been discussed by Müller (1929, 1931), Oosterkamp (1948), and Ishimura *et al.* (1957). The later calculations are in adequate agreement with Müller's results, from which the power W for a copper target is given by

$$W = 26.4 f_1 (f_2 \nu)^{1/2}.$$

Here, W is in watts, f_1 and f_2 are the length and the width of the focal line in mm, and ν is the linear speed of the target surface in mm s^{-1}; it is assumed that the surface temperature of the target reaches 600 °C, well below the melting point of copper (1083 °C). Thus, for a focal spot 1.5×0.15 mm and for an 89 mm-diameter target rotating at 6000 revolutions min^{-1} (ν = 28 000 mm s^{-1}), Müller's formula gives a maximum permissible power loading of 2.5 kW or 57 mA at 45 kV. This agrees well with the experimentally determined loading limit.

Green & Cosslett (1968) have made extensive measurements of the efficiency of the production of characteristic radiation for a number of targets and for a range of electron accelerating voltages. Their results have been verified by many subsequent investigators. For a copper target, they found that the number of $K\alpha$ photons emitted per unit solid angle per incident electron is given by

$$N/4\pi = 6.4 \times 10^{-5} [E/E_k - 1]^{1.63},$$

where E is the tube voltage in kV and E_k = 8.9 keV is the K excitation voltage.

Accordingly, the number of $K\alpha$ photons generated per second per steradian per mA of tube current is 1.05×10^{12} at 25 kV and 4.84×10^{12} at 50 kV.

Of the generated photons, only a fraction, usually denoted by $f(\chi)$ (Green, 1963), emerges from the target as a result of X-ray absorption in the target. $f(\chi)$ decreases with increasing tube voltage and with decreasing take-off angle. It has a value of about 0.5 for E = 50 kV and for a take-off angle of 5°.

The X-ray beam is further attenuated by absorption in the tube window (~80% transmission), by the air path between the tube and the sample, and by any β-filters which may be used.

In a typical diffractometer or image-plate arrangement where no beam conditioning other than a β-filter is employed, the sample may be 300 mm from the tube focus and the limiting aperture at that point might have a diameter of 0.3 mm, so that the full-angle cross fire at the sample is 1.0×10^{-3} rad. The solid angle subtended by the limiting aperture at the source is 7.9×10^{-7} steradians. At 50 kV and 60 mA, the X-ray flux through the sample will be approximately 4.5×10^7 photons s^{-1}. These figures are approximately confirmed by unpublished experimental measurements by Arndt & Mancia and by Faruqi & Leslie. It is interesting to note that the power in this photon flux is 5.8×10^{-8} W, which is a fraction of 2×10^{-11} of the power loading of the X-ray tube target.

Instead of simple aperture collimation, one of the types of focusing collimators described in Section 6.1.4.1 below may be used. They collect a somewhat larger solid angle of radiation from the target of a conventional X-ray source than does a simple collimator and some produce a higher intensity at the sample.

6.1.2.3. *Microfocus X-ray tubes*

Standard sealed X-ray tubes with a stationary target deliver a collimated intensity to the sample which is insufficient for most applications in macromolecular crystallography. These tubes have foreshortened foci between 0.4 and 2 mm^2 which do not lend themselves to efficient collimation by means of focusing mirrors or monochromators without introducing a cross fire in the beam that is too large for our purposes.

The situation is different with microfocus tubes, which are discussed in Section 6.1.4.2. Here, a relatively large solid angle of collection can make up for the lower power dissipation which results from the small electron focus.

6.1.2.4. *Synchrotron-radiation sources*

Charged particles with energy E and mass m moving in a circular orbit of radius R at a constant speed ν radiate a power, P, into a solid angle of 4π, where

$$P = 88.47 E^4 I/R,$$

where E is in GeV, I is the circulating electron or positron current in ampères and R is in metres. Thus, for example, in a bending-magnet beam line at the ESRF, Grenoble, France, R = 20 m, and at 5 GeV and 200 mA, P = 554 kW.

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.* 0.1 mrad for E = 5 GeV (Fig. 6.1.2.2). This fan rotates with the 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 ~9% of the total number of photons, is at $\lambda < \lambda_c$ (Fig. 6.1.2.6). λ_c (in Å) is given by

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

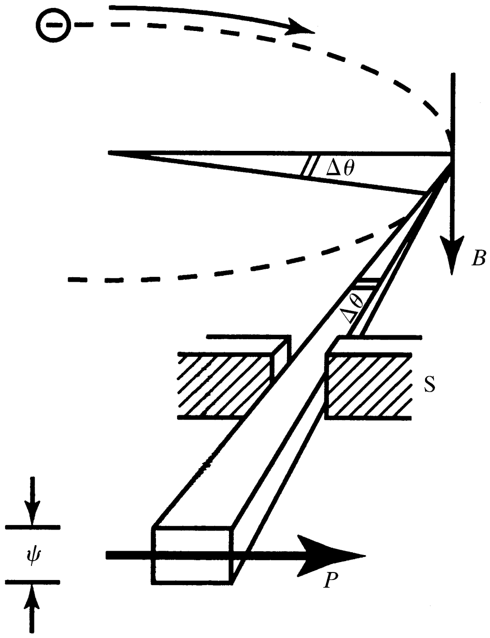

Fig. 6.1.2.2. Synchrotron radiation emitted by a relativistic electron travelling in a curved trajectory. B is the magnetic field perpendicular to the plane of the electron orbit; ψ is the natural opening angle in the vertical plane; P is the direction of polarization. The slit, S, defines the length of the arc of angle, $\Delta\theta$, from which the radiation is taken. From Buras & Tazzari (1984).

references