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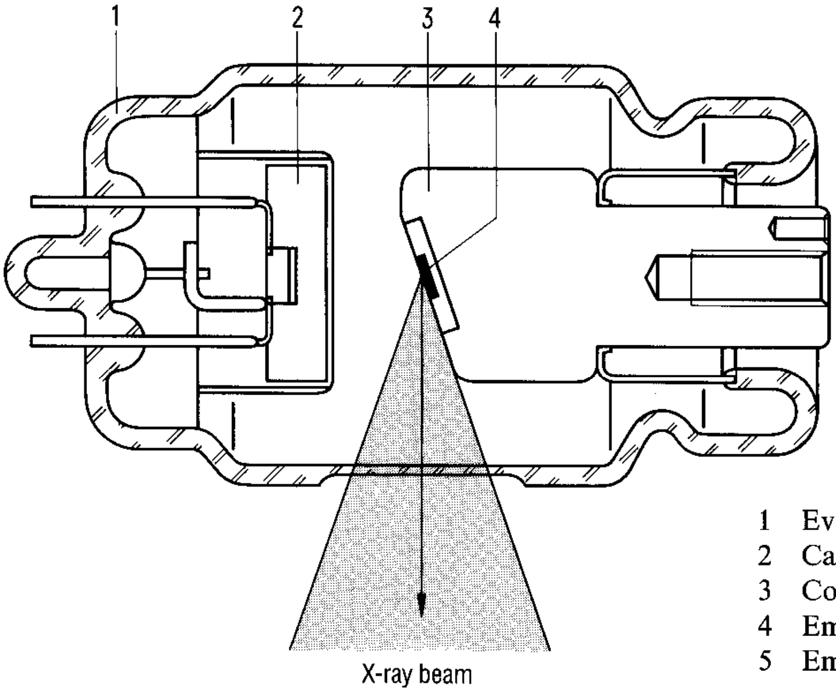
7.1 Image generation

7.1.1 The x-ray tube

As the source of radiation in the x-ray apparatus, the x-ray tube has a decisive influence on the image quality of the system. The following properties are of crucial importance:

- ▻ The hardness of the radiation, i.e. its penetration capacity, may be varied over a wide range by means of the magnitude of the voltage applied to the tube and thus may be optimally adapted to the object to be examined and to the method of examination.
- ▻ The radiation intensity (dose rate) may also be controlled over a wide range via the tube current.
- ▻ Finally, the focal spot size and the energy distribution in the focal spot are determining factors for the modulation transfer function (MTF) of the radiation source and thus contributing factors to the contrast and the resolving power.

The principle of the design of an x-ray tube can be taken from the example of the cross-section of the tube SR 70/7 used in dental x-ray units (Fig. 7.1): An evacuated envelope (1), which here simultaneously performs the task of high voltage insulation, contains the cathode assembly (2) and the anode (3) situated opposite one another. The electrons which are released and focussed in the cathode assembly are accelerated by the applied high voltage to 30



1	Evacuated glass envelope
2	Cathode
3	Copper anode
4	Embedded tungsten target
5	Emerging radiation

Fig. 7.1 Cross-section of the SR 70/7 stationary anode tube (HELIODENT)

to 65% of the speed of light [7.1] (Fig. 7.2), and abruptly decelerated in the tungsten target (4) in the anode. In this process, as described in section 3.1, less than 1% of the electron energy is converted into x radiation; by far the largest part has to be dissipated as waste heat.

The individual assemblies in the x-ray tube will be treated in detail in the following sections.

Cathode assembly

In the vast majority of x-ray tubes used today, the cathode assembly consists of two parts: the electron source, usually a directly-heated helically-wound tungsten wire of 0.2 to 0.3 mm diameter, and an auxiliary electrode surrounding this (Wehnelt electrode). Other systems, for example multiple electrode systems with dispenser cathodes (electron guns), have up to now been confined to special applications because of their complex construction [7.2].

Electron emission

We begin with some basic remarks about the properties of a tungsten wire as an electron emitter. Apart from depending on the geometrical dimensions and the material constants, the number of electrons emitted from a metal depends in the first instance on the temperature. The emission current density

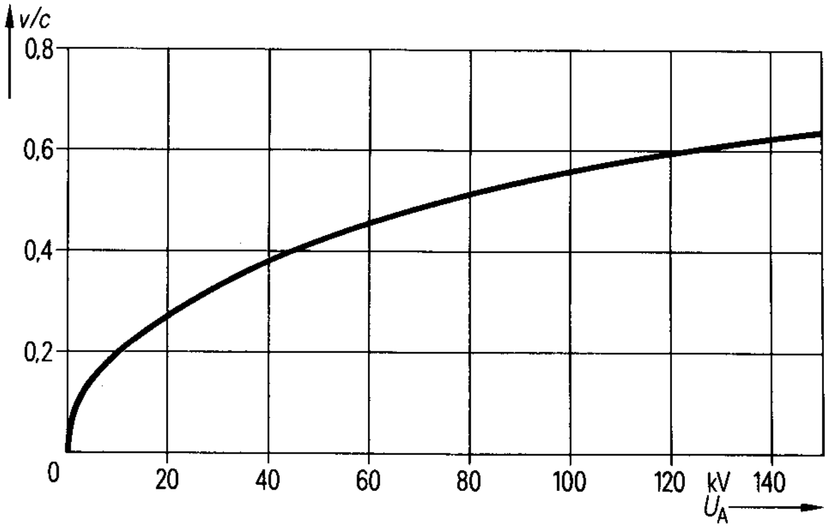


Fig. 7.2
Ratio of the electron velocity v to the speed of light c as a function of the anode voltage (acceleration voltage) U_A

j_e as a function of temperature is given by the Richardson equation

$$j_e = A_0\, T^2\, e^{-\frac{W}{kT}} \tag{7.1}$$

W Work function, for tungsten $= 4.5$ eV
k Boltzmann constant
T Temperature
A_0 Material constant, for tungsten $\approx 60\, \frac{A}{\mathrm{cm}^2\, \mathrm{K}^2}$

and is depicted for tungsten in Fig. 7.3.

In order to obtain the currents of a few 100 mA up to 2 A required for x-ray images, emitter temperatures around 2700 K are needed. At such high temperatures a noticeable evaporation of the metal can be observed even for tungsten, which has a high melting point. This evaporation leads to the shortening of the life of the emitter, on the one hand via the deposition of metal on the inside of the glass envelope with consequent impairment of insulation, and, on the other hand, in a direct way due to the filament melting (Fig. 7.4). Because of this the filament is heated to the emission temperature only for the short exposure period. In order to keep the time until the emission temperature is reached below 1 s, the emitter is preheated to around 1500 K. At this temperature, there is so little metal evaporation that no negative effects on the useful life of the tube can be observed.

Anode current

The electrons, emerging with a low velocity from the emitter, form an electron cloud around it. They are accelerated towards the anode by the applied high voltage. Since the electron cloud partially screens the electric field generated, however, only a portion of the electrons are affected at low voltages. This then gives the characteristic curves depicted in Fig. 7.5 for the anode current.

For low voltages, the space charge law applies

$$I_A = \frac{4}{9}\, \varepsilon_0 \sqrt{2\frac{e}{m}} \cdot \frac{U_A^{3/2}}{d^2}, \tag{7.2}$$

I_A Anode current
ε_0 Permittivity of vacuum
e Electron charge
m Electron mass
U_A Anode potential
d Distance between cathode and anode

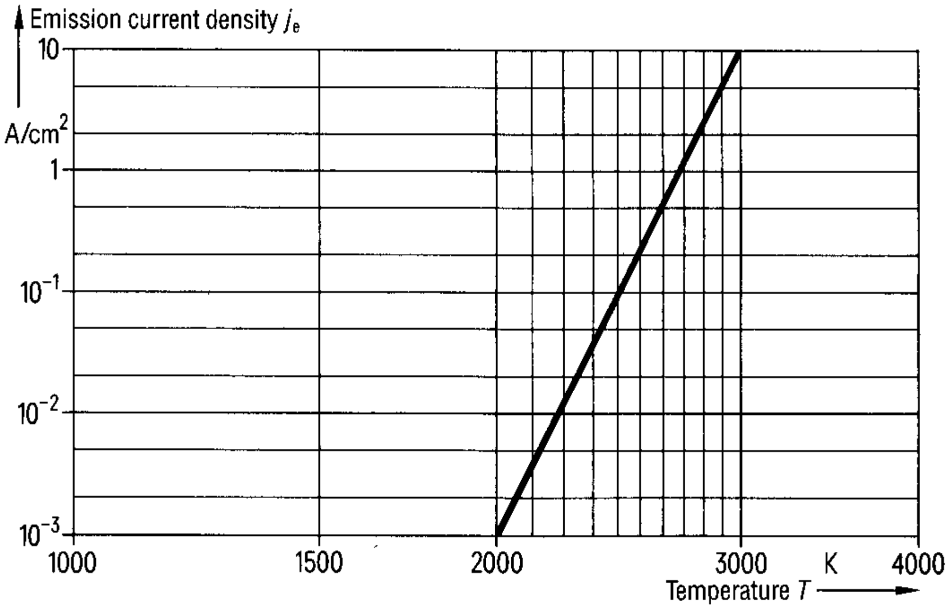


Fig. 7.3 Emission current density j_e as a function of the temperature T for tungsten

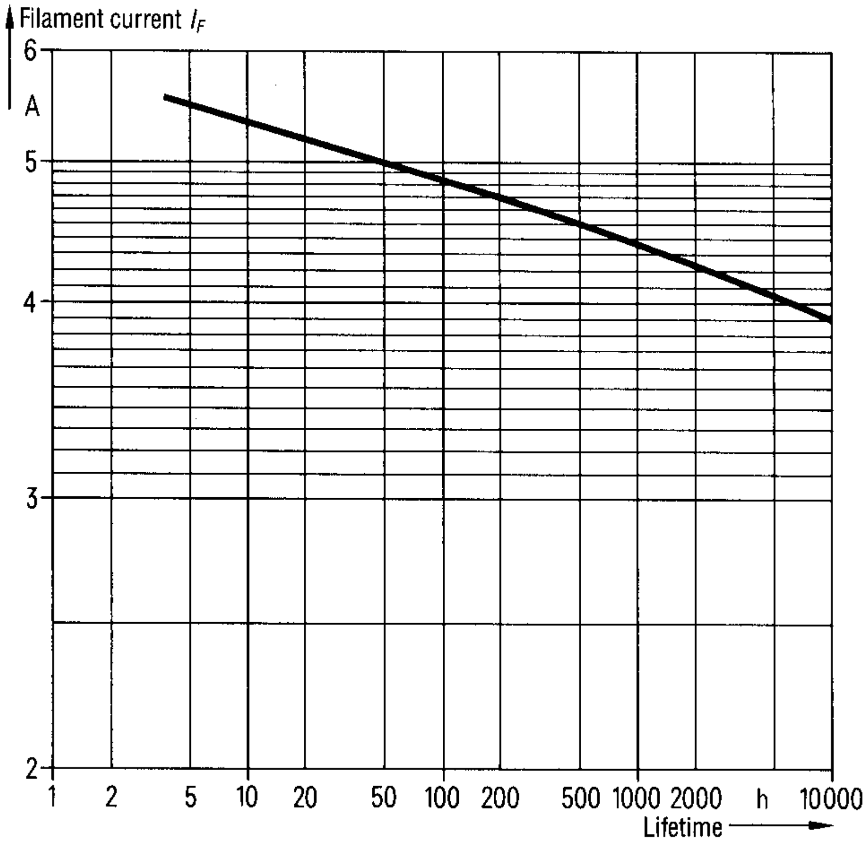


Fig. 7.4

Lifetime of a 0.2 mm diameter tungsten wire as a function of filament current. For radiography, filament currents are around 5 A, for fluoroscopy, filament currents are below 4 A.

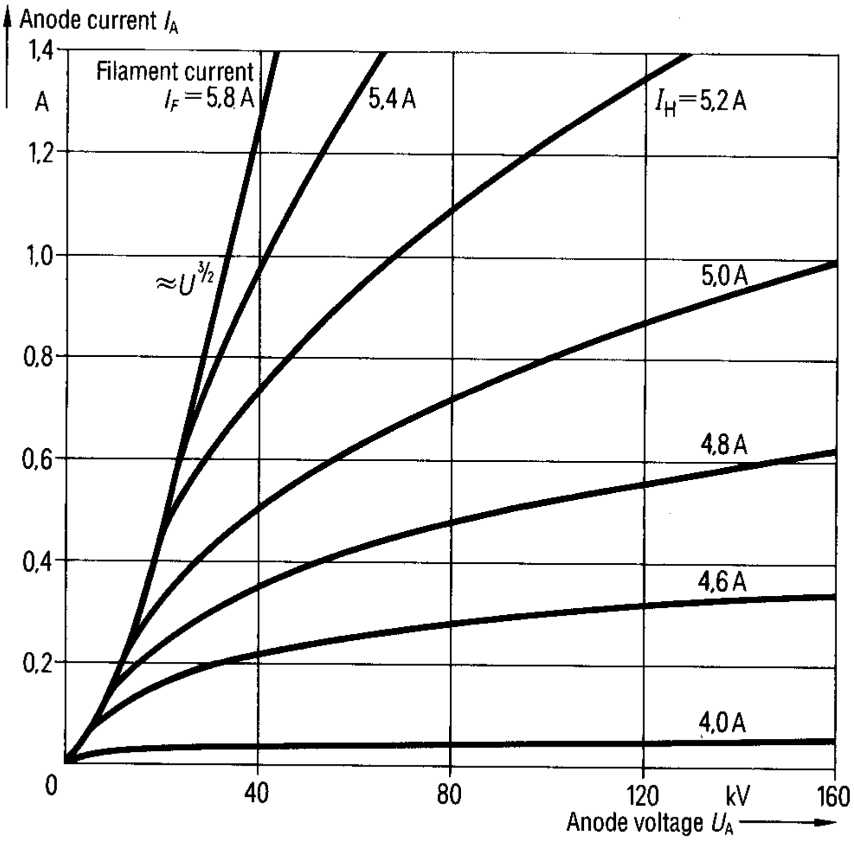


Fig. 7.5
Anode current I_A as a function of anode voltage U_A with the filament current I_F as a parameter

however, only as long as the electron density around the cathode is sufficiently high. For high anode potentials, all the electrons emitted are drawn off and one obtains the saturation current from emitter surface and current density according to the equation:

$$I_S = j_e \cdot A_E. \tag{7.3}$$

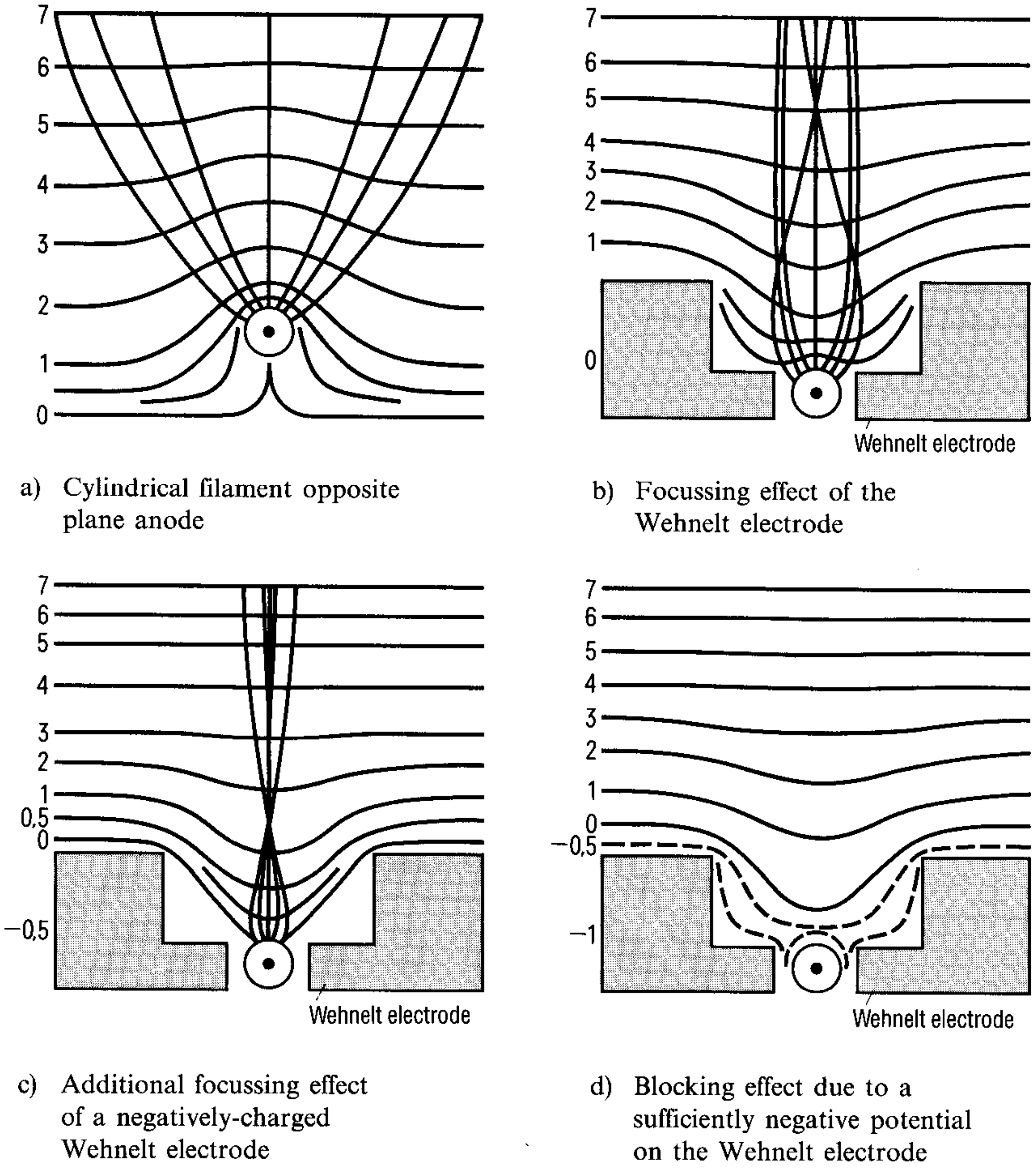
j_e Emission current density following equation (7.1)
A_E Emitter surface
I_S Saturation current

In this region, the current virtually only depends on the cathode temperature and consequently on the filament power: because of high field strengths in front of the emitter, the work function is reduced (Schottky effect). For x-ray tubes, this in fact still leads to a slight dependence of the saturation current on the anode potential, but may be ignored in the range <5%. Further details may be found in the literature, e.g. in [7.1].

Focussing

If additional measures were not taken, the electrons emitted from the cathode and accelerated towards the anode would hit the anode in a widely smeared-out distribution, and would thus cause the x radiation to be created over a large area, which would lead to blurred images (Fig. 7.6a).

By means of an extra electrode of a suitable shape arranged around the cathode (Wehnelt electrode) and at the cathode potential, the path of the equipotential lines can be changed in such a way that the electrons are focussed at the



a) Cylindrical filament opposite plane anode

b) Focussing effect of the Wehnelt electrode

c) Additional focussing effect of a negatively-charged Wehnelt electrode

d) Blocking effect due to a sufficiently negative potential on the Wehnelt electrode

Fig. 7.6
Theoretical variation of the equipotential lines (relative potential values: 0 to 7) and electron trajectories

focal spot by the forces directed towards the central line joining cathode and anode (Fig. 7.6b). If the Wehnelt electrode is given an additional negative potential, this effect can be enhanced (Fig. 7.6c). It is, of course, a prerequisite that the geometry of the Wehnelt electrode, the emitter and the separation from the anode are optimally adapted to one another.

Furthermore, an electrode with a negative bias relative to the cathode provides an additional means of controlling the anode current, since, as can be seen from Figs. 7.6b and c, the field strength in front of the emitter is changed. In practice, however, this is only used in the case of x-ray tubes for switching on and off by means of a grid voltage (Fig. 7.6d) (grid pulsed operation) in the case of particularly short pulse times and fast pulse sequence frequencies.

A drawback of the Wehnelt electrode is that the effect of the anode potential on the emitter is reduced. The saturation value of the current is, therefore, only reached at higher anode potentials. At low anode potentials, especially for strongly focussed small focal spots, this arrangement operates in a part of the characteristic which is still essentially space-charge limited. This restricts the anode current. The attempt to achieve a greater anode current through increased heating of the emitter leads to the admissible temperatures being exceeded and thus to the emitter's destruction (Fig. 7.7).

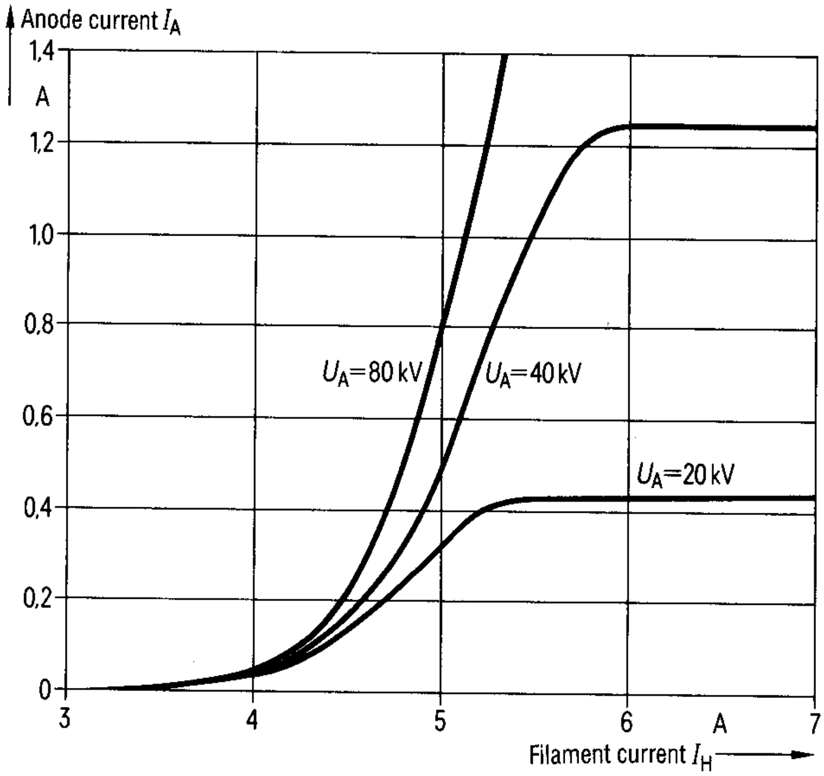


Fig. 7.7
Anode current I_A as a function of the filament current I_H with the anode voltage U_A as a parameter

Geometry of the focal spot

The area covered by the electrons and their distribution over the anode determine the size and structure of the focal spot, whose effective size is obtained from its projection in the imaging direction (Fig. 7.8).

It is thus immediately clear that for the various zones of a large-area image, differing focal spot sizes come into effect (Fig. 7.9).

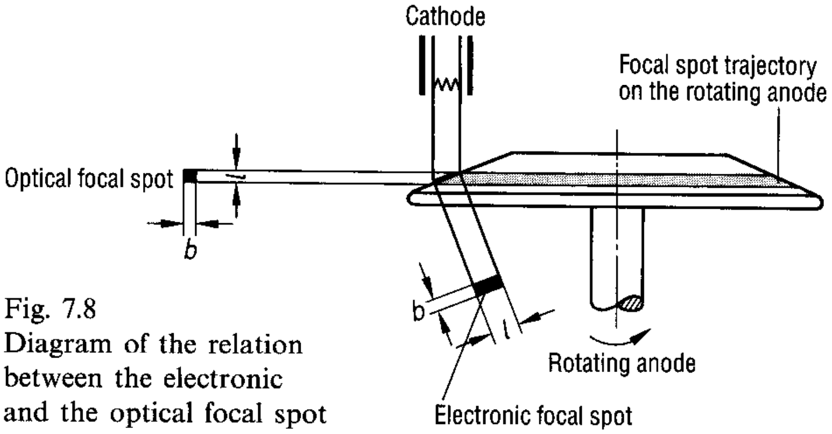


Fig. 7.8
Diagram of the relation between the electronic and the optical focal spot

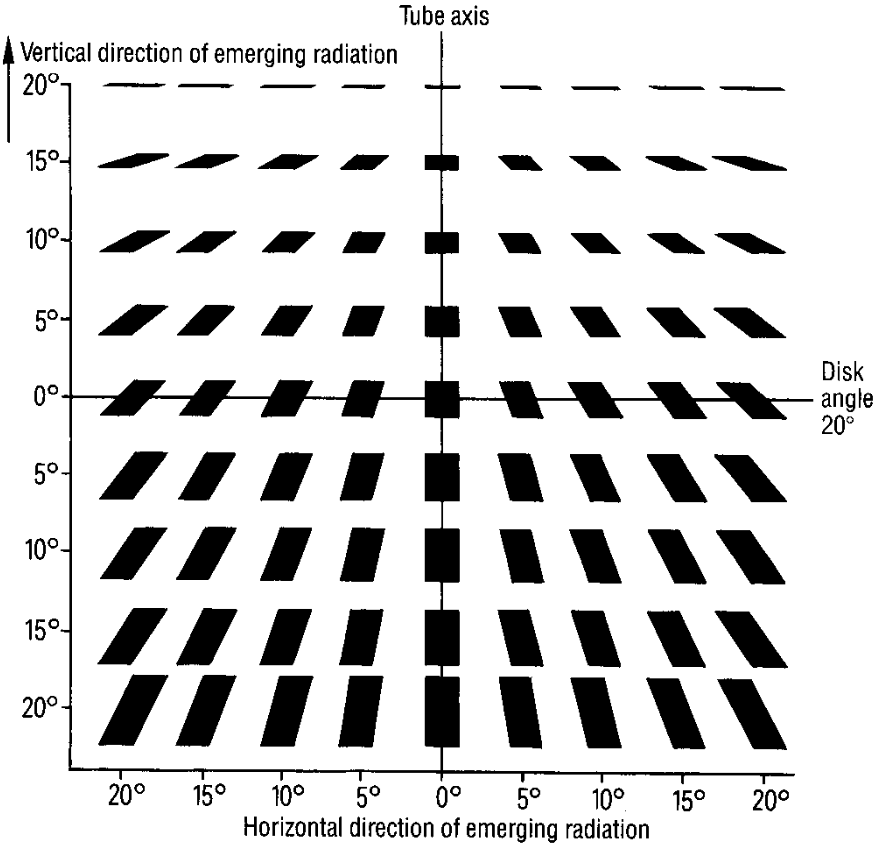


Fig. 7.9
Variation of focal spot geometry and size in various directions away from the center of radiation. Here the center of radiation is located perpendicular to the intersection of the axes and is pointing towards the observer

Usually the projection perpendicular to the tube axis is given as the focal spot size.

The focal spot size can be determined most easily with the aid of a pinhole image (Fig. 7.10). For more exact analyses of the focal spot with respect to its properties, however, narrow slits in the two major axes of the focal spot are used instead of the pinhole (Figs. 7.11 and 7.12). The images so obtained can be analyzed with a photometer so that one gets an image of the intensity distribution of the x rays in the focal spot. By means of a Fourier transform, the modulation transfer function, MTF, is obtained from this intensity distribution curve, being the fundamental measure of the imaging properties of the focal spot. It describes the contrast (in %) as a function of resolution (line pairs/mm).

As an example, Figs. 7.10 to 7.13 show the various quantities for the focal spot of an x-ray tube.

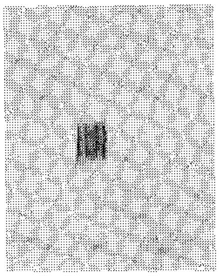


Fig. 7.10
Pinhole camera image
of a 100 kW focal spot

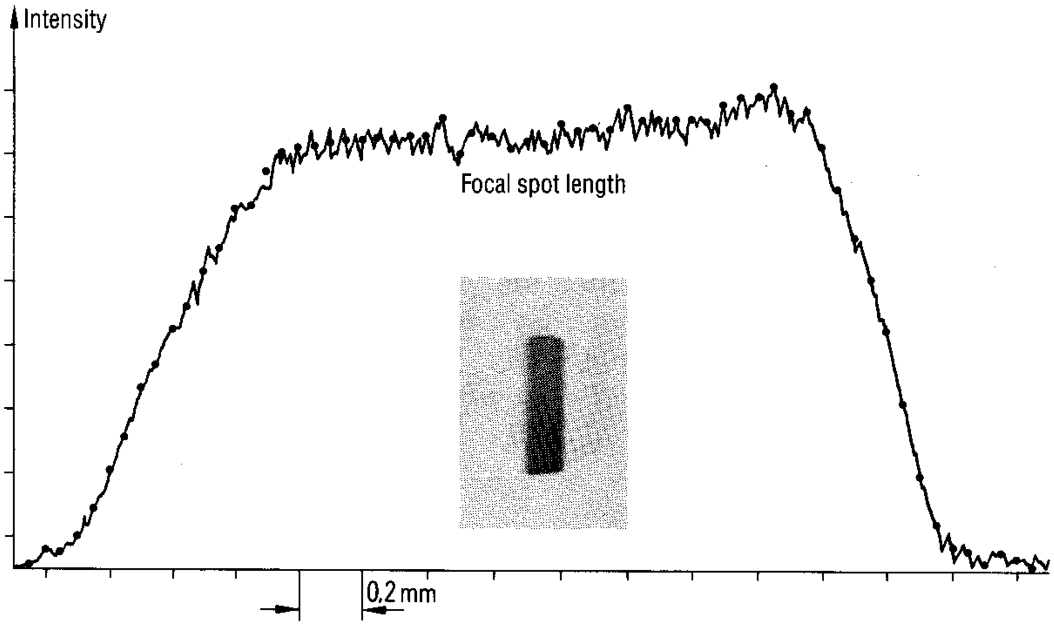


Fig. 7.11
Slot camera image of the length of the focal spot in Fig. 7.10 and photometric analysis

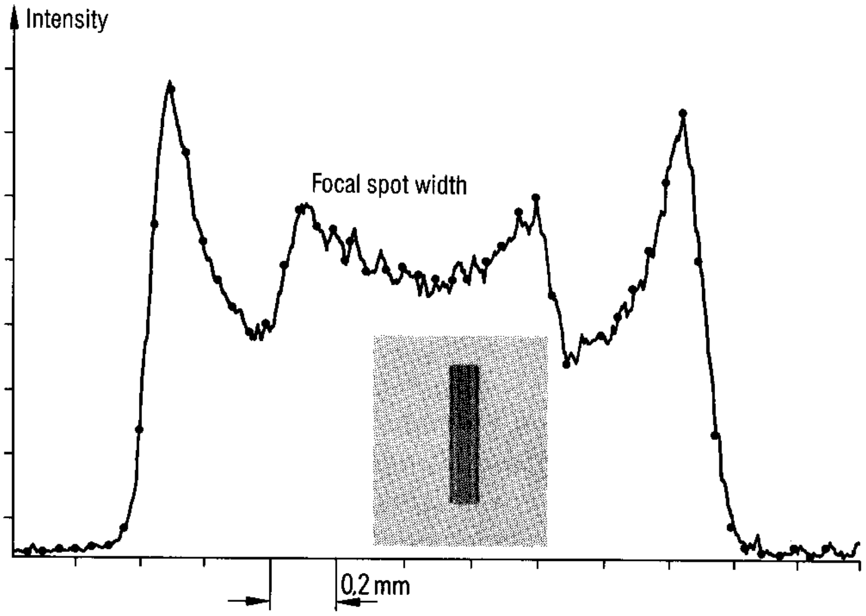


Fig. 7.12
Slot camera image of the width of the focal spot in Fig. 7.10 and photometric analysis

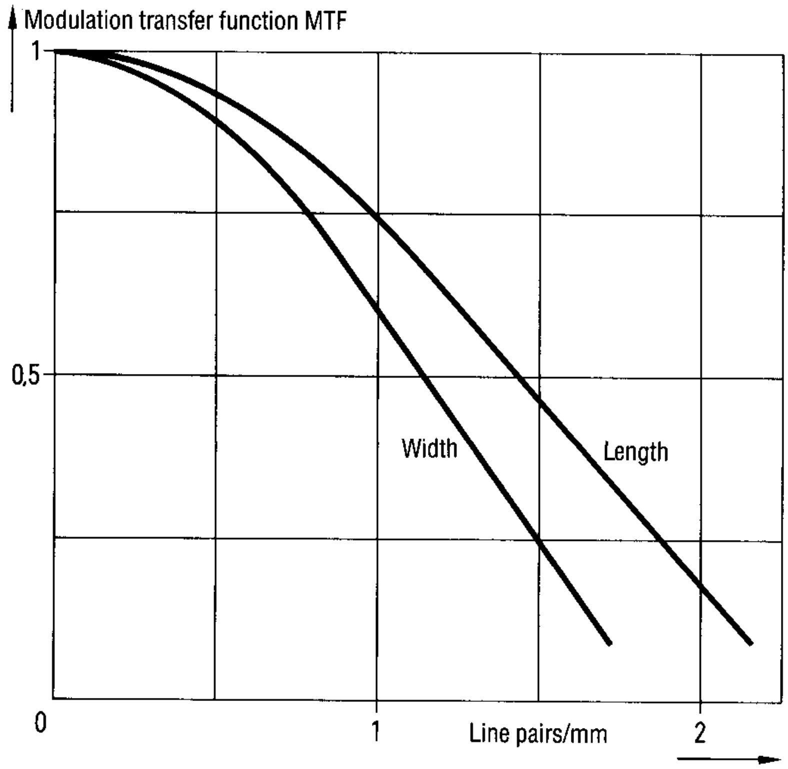


Fig. 7.13
Modulation transfer function calculated from the photometer curves of Figs. 7.11 and 7.12 for an imaging ratio of 1:1.3

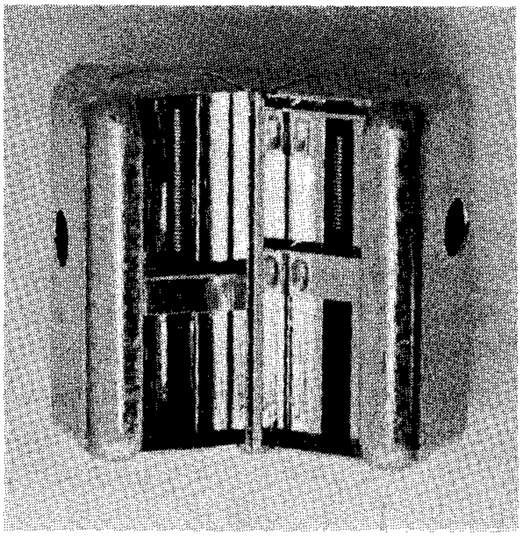


Fig. 7.14
Focusing head with two parallel emitters for focal spots of 0.6 and 1.2 mm projected one inside the other and for powers of 40 and 100 kW

Most x-ray tubes offer the possibility of working with two or more focal spots. The reason for this is that a simultaneous optimization of the size of the focal spot to achieve both high resolution and high power cannot be realized because of the limitations due to the properties of the anode material. Thus, in the case of two focal spots, which may be arranged one behind the other or next to each other, one will be designed for high resolution, and the other for high power. The construction of such cathodes for focal spots with 40/100 kW power and 0.6 and 1.2 mm focal size respectively, lying superimposed upon each other on the disk, is shown in Fig. 7.14.

Extrafocal radiation

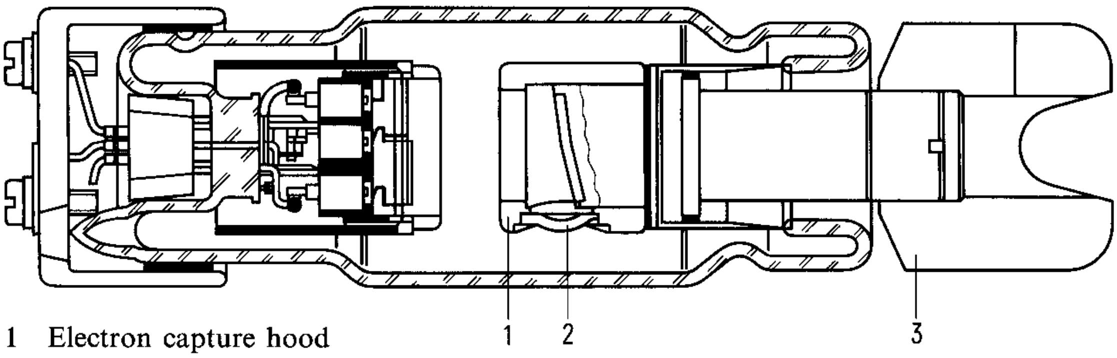
A not inconsiderable proportion of the electrons which hit the anode leaves it again. Some of these electrons are scattered backwards elastically, i.e. without loss of energy, enter the opposing field between cathode and anode and fall back onto the anode, but outside the original focal spot. In this way extrafocal radiation is created outside the focal spot which in certain circumstances may also have a negative influence on the image quality if it is generated in the immediate vicinity of the focal spot and thus cannot be screened out. By arranging the tube assembly in an appropriate way, one aims to achieve electrical field distributions in the critical region of the anode which counteract this effect.

Anode assembly

In the following, the design characteristics of various kinds of anode are described; loading capacity is dealt with at the end of this section. From what was said in section 3.1.3, it follows that tungsten is the most suitable target material for use in x-ray diagnostics; only in the special case of mammography is molybdenum sometimes preferred. Because of the low efficiency of the conversion of the electrons' kinetic energy into x radiation, more than 99% of the energy introduced into the x-ray tube has to be carried off in the form of heat. The problems to be solved are those of the heat distribution in the anode and of the dissipation of the heat to the surroundings.

Stationary anodes

The tungsten target is embedded in a copper block. The heat is carried away by conduction via the stem to the surroundings. One method (which, however, is hardly ever used for diagnostic x-ray tubes) is to create additional convection by means of cooling boreholes in the anode block, through which water or oil is then pumped for cooling. The anode frequently has an electron capture hood with a beryllium window which lets through radiation easily, and this prevents the electrons which are reflected at the target from reaching the glass envelope and thus adversely affecting the disruptive strength of the tube. Because of the field-free space in front of the target, this design also largely stops the reflected electrons falling back and so reduces the undesirable extrafocal radiation. Stationary anode x-ray tubes are admittedly very reliable because of the simplicity of their construction; however, for many applications they are not suitable because of the power limit in the focal spot on the anode. The upper power limit is reached in particular for radiography by the temperature at the boundary between the tungsten target and the copper exceeding the melting point of copper. The maximum load for radiography is around 100 W/mm^2, and in continuous operation (fluoroscopy) it is 30 W/mm^2. Fig. 7.15 shows a cross-section of a typical stationary anode x-ray tube, the x-ray tube SRL 90/10/30.



1 Electron capture hood
2 Beryllium window
3 Copper cooling block

Fig. 7.15 Cross-section through the SRL 90/10/30 stationary anode x-ray tube

Rotating anodes

The idea of letting the anode rotate in order to raise the rating occurred very early on. This first suggestion, which was made by Wood in 1897, was that the glass bulb should rotate as an anode around the cathode, which was also mounted so that it could rotate (Fig. 7.16). The actual technical realization of this idea, however, did not come about until 1929 with the advent of the rotating metal anode and the introduction in 1933 of the freely rotating anode disk made out of tungsten.

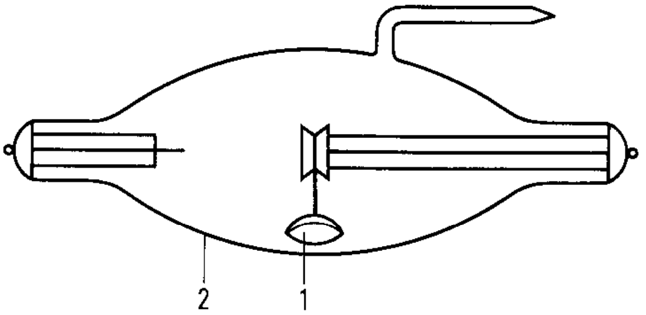
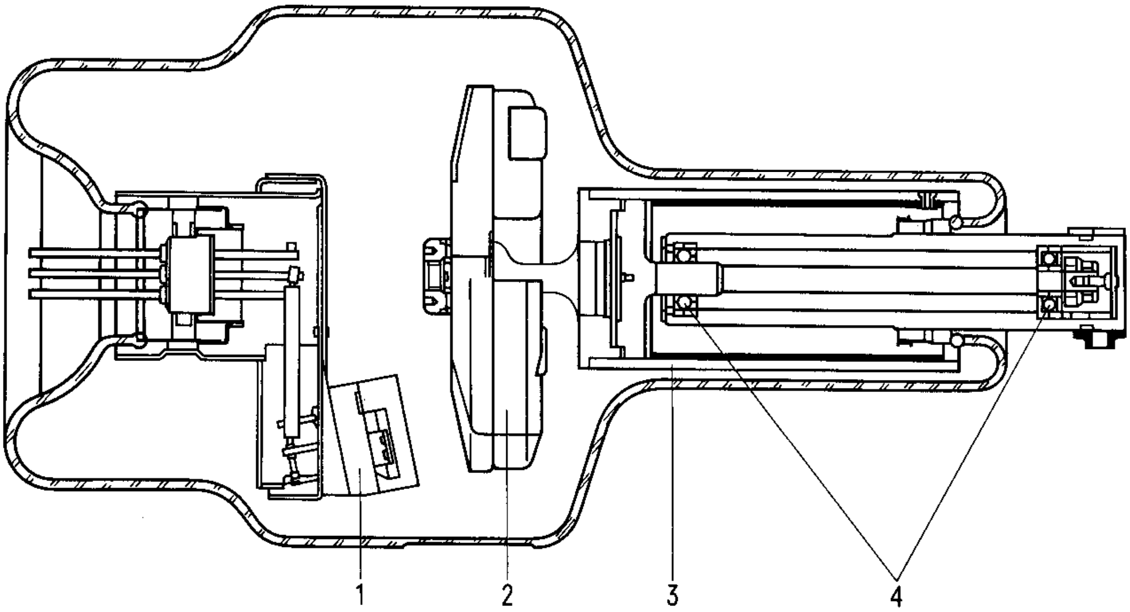


Fig. 7.16
The first idea for a 'rotating anode x-ray tube' by Wood in 1897. The cathode (1) is supported by bearings so as to be free to rotate inside the glass bulb (2), which functions here as the anode. It is held in position by gravity



1 Dual focus cathode
2 Graphite-RTM compound anode
3 Rotor
4 Ball bearings

Fig. 7.17 Cross-section through a rotating anode x-ray tube

The construction of a modern rotating anode x-ray tube is shown in Fig. 7.17. It is powered with the aid of the rotor (3) made to act as a squirrel-cage rotor by means of the rotating field, which is generated by a stator outside the vacuum. The standard number of revolutions is around 3,000 r.p.m. and 9,000 r.p.m. respectively. For special applications with extremely high intensities in the focal spot, 17,000 r.p.m. are required. In these circumstances, operating in the vacuum and at high temperatures, the ball bearings have to satisfy exceptional demands.

The highest thermomechanical demands are placed on the anode disk. Originally it was made out of pure tungsten. Because of its restricted rating and lifetime, at the very least a rhenium-tungsten-molybdenum (RTM) compound anode (Fig. 7.18 a) is used in x-ray tubes nowadays. By alloying a few parts of rhenium to tungsten, an improvement in the elastic properties and hence a substantially improved resistance to wear of the 1 to 2 mm thick covering layer are achieved (Fig. 7.18 d). A disk base made of molybdenum gives an increased heat capacity compared to a tungsten anode with the same mass [7.11, 7.12].

The graphite RTM composite anode (Fig. 7.18 b) represents a further advance in anode technology. This technology enabled the heat capacity and heat loss by radiation of the anode to be raised considerably. In modern high power x-ray tubes, as used for example in computed tomography, the CALOREX anode with a heat capacity of up to 2×10^6 Ws and a thermal dissipation power of up to 5 kW is exclusively used (7.18 c).

Vacuum envelope

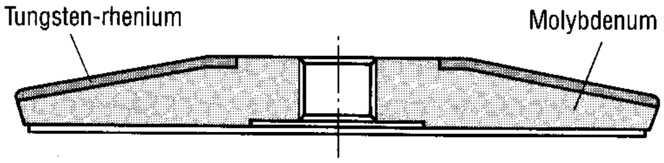
The vacuum inside an x-ray tube must meet the following requirements:

- It must be good enough to guarantee the insulation of the high voltage between the anode and the cathode.
- The electrons must be able to travel from cathode to anode without colliding with atoms of residual gas.
- The cathode surface must not be adulterated by the atoms of residual gas, in order to ensure the reproducibility and constancy of the emission currents.
- The vacuum must be maintained throughout the entire life of the x-ray tube.

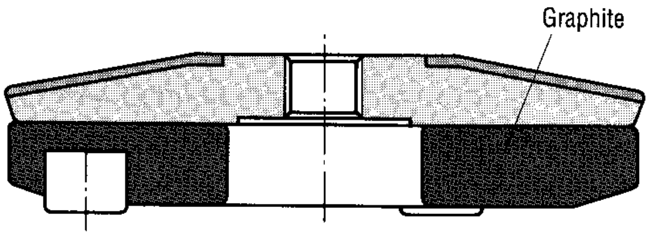
Besides selecting suitable electrode materials readily susceptible to de-gassing, a prerequisite for generating and maintaining a vacuum of at least 10^{-5} mbar is an appropriate vacuum envelope. Apart from the technical requirements relating purely to maintaining a vacuum, the envelope should also fulfil the

is an appropriate vacuum envelope. Apart from the technical requirements

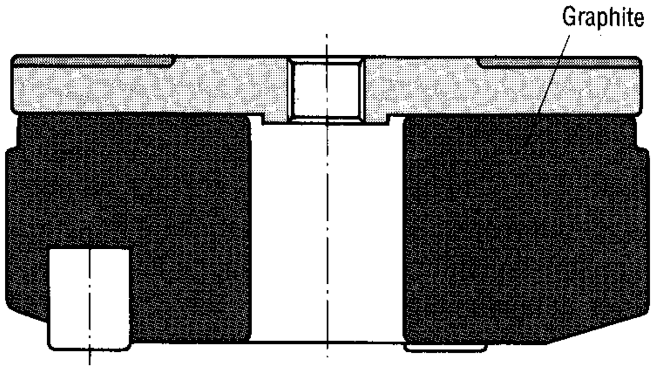
Fig. 7.18
Comparison of the heat capacities of RTM and RTM-graphite anodes



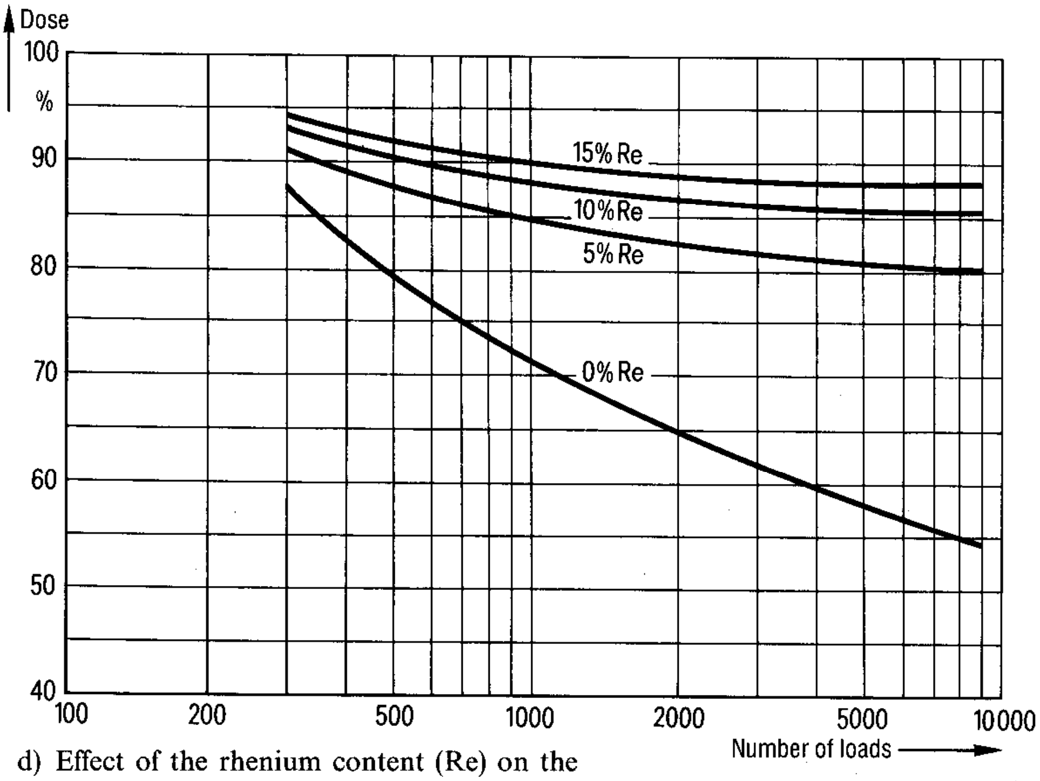
a) RTM anode for 250,000 Ws



b) RTM-graphite anode for 400,000 Ws



c) RTM-graphite anode for 1,000,000 Ws
(for computer tomographs)



d) Effect of the rhenium content (Re) on the resistance to wear and tear of the tungsten anode covering layer following conditions:

- ▻ low x-radiation absorption,
- ▻ high temperature cycle resistance
- ▻ high insulation capacity, at least in those cases where it simultaneously takes care of the insulation of the cathode and anode,
- ▻ high permeability to radiated heat.

Glass satisfies all these requirements almost ideally, which is why up to this day glass has predominantly been used as the vacuum envelope for x-ray tubes (Fig. 7.17).

A drawback of the glass envelope construction is the deterioration of its insulating capacity due to vaporization from the anode and cathode, which is virtually unavoidable and which leads to metal deposits on the glass surface. One tries to overcome this disadvantage by using an appropriate design in which the central part of the tube is made of metal. Designs in which the entire vacuum envelope is made of metal and the insulation achieved using ceramic insulators in the anode and cathode assemblies aim to avoid the same problem. It is necessary to weigh up which design is preferable in each particular case, taking into account all the parameters pertaining to the operation of the tube.

X-ray tube assembly

In order to ensure the safe operation of the x-ray tube it is enclosed in a protective casing. Two kinds of design should be distinguished, the simple x-ray tube assembly (Fig. 7.19), which, apart from the tube, only houses the stator and a few control components, and the single-tank x-ray tube assembly. In the single-tank assembly, the tube is integrated with the high voltage generator. This kind of x-ray tube assembly was originally used almost exclusively for stationary anode x-ray tubes, but in the meantime has become very important for rotating anode tubes as well, because of the application of high frequency technology in generating high voltage.

The tube casing performs the following functions:

- ▻ high voltage insulation
- ▻ cooling
- ▻ protection against implosion
- ▻ protection against radiation.

The radiation protection in particular must be checked for each individual x-ray tube assembly by means of a suitable 4 π-measurement (Fig. 7.20).

The measurement is carried out as follows. The x-ray tube assembly is operated in the center of a C-arc of 2 m diameter which is fitted with ionization chambers.

By rotating the assembly, the entire volume is measured. Each time the chamber with the highest reading is electronically selected and recorded.

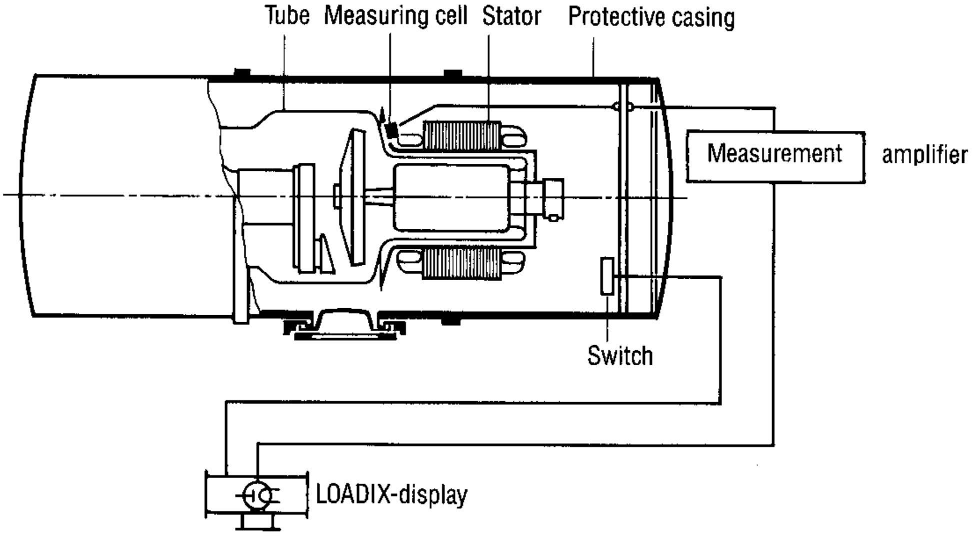


Fig. 7.19
The x-ray tube assembly consists of the protective casing and the built-in x-ray tube. The diagram also shows an instrument for monitoring the anode disk temperature (LOADIX)

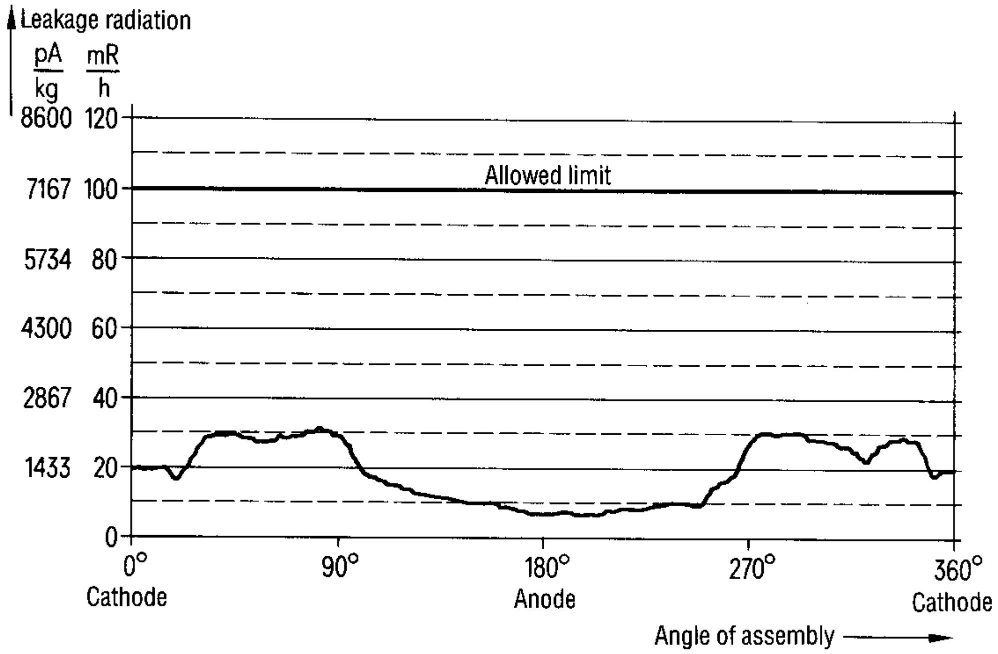


Fig. 7.20
Leakage radiation from a high power x-ray tube assembly. The measured values lie clearly below the allowed limits

Load capacity of x-ray tubes

The load capacity of x-ray tubes in operation is determined by the rapid rise in temperature in the focal spot. Fundamental work was done on this subject by Bouwers [7.3] and Osterkamp [7.4] for stationary anodes. The rise in temperature in this case for short load times (<0.05 s for standard focal spot dimensions) is given approximately by

$$\vartheta = \frac{2P}{A}\sqrt{\frac{t}{\pi \cdot \lambda \varrho c}} \tag{7.4}$$

P	Power input	λ	Thermal conductivity
A	Focal spot area	c	Specific heat
t	Load period	ϱ	Density

and for long load periods by

$$\vartheta = \frac{P \cdot R}{A \cdot \lambda}. \tag{7.5}$$

R Smallest dimension of the focal spot.

Once again it should be pointed out that in the case of a stationary anode tube a significantly lower value should be used for the maximum permissible focal spot temperature than that which follows from equation (7.5), since in this case the admissible temperature at the boundary between tungsten and copper would be exceeded. Furthermore, for very long load periods a further limit which is obtained from the thermal capacity of the anode and the thermal dissipation to the surrounding oil must often be taken into account.

With respect to rotating anodes, the focal spot temperature may be written following [7.5, 7.6, 7.7] as the sum of basic disk temperature θ_0, focal ring temperature θ_{v0} and temperature rise θ_R after several turns n of the rotating anode (Fig. 7.21):

$$\vartheta_{n0} = \vartheta_0 + \vartheta_{v0} + \vartheta_R.$$

Here the temperature rise may be calculated according to the equation (7.4) already given for the stationary anode, if for the load period one inserts the appropriate length of time a disk element with focal spot width $2\,\delta$ stays in the electron beam. Given the mean focal track radius R and rotation frequency f, one then has:

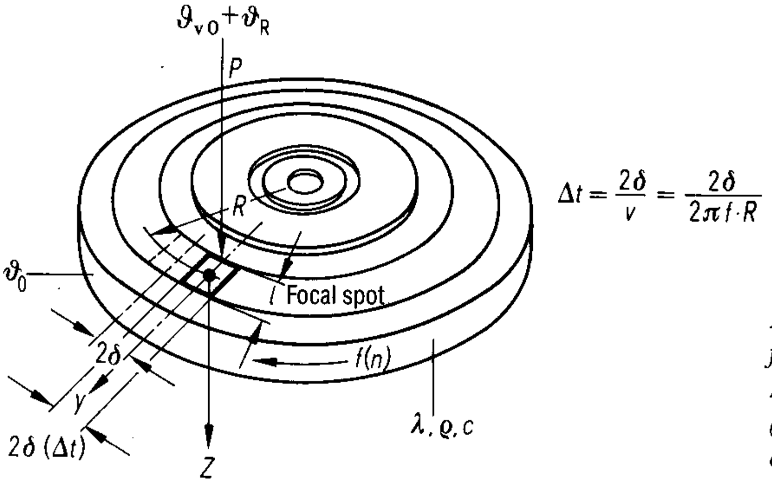
$$\Delta t = \frac{\delta}{\pi \cdot R \cdot f} \tag{7.7}$$

or using equation (7.4)

$$\vartheta_\mathrm{R}=\frac{2P}{A}\sqrt{\frac{\delta}{\pi^2\cdot f\cdot R\cdot\lambda\cdot\varrho\cdot c}}. \tag{7.8}$$

The focal ring temperature is described by

$$\vartheta_{\mathrm{v}0}=k\,\vartheta_\mathrm{R}\sqrt{\frac{\delta}{\pi R}}\sqrt{n+1} \tag{7.9}$$



T	time for one revolution
A	Focal spot area ($2\delta l$)
f	Rotation frequency
λ	Thermal conductivity
ϱ	Density
c	Specific heat

Fig. 7.21 Geometrical relations at the rotating anode

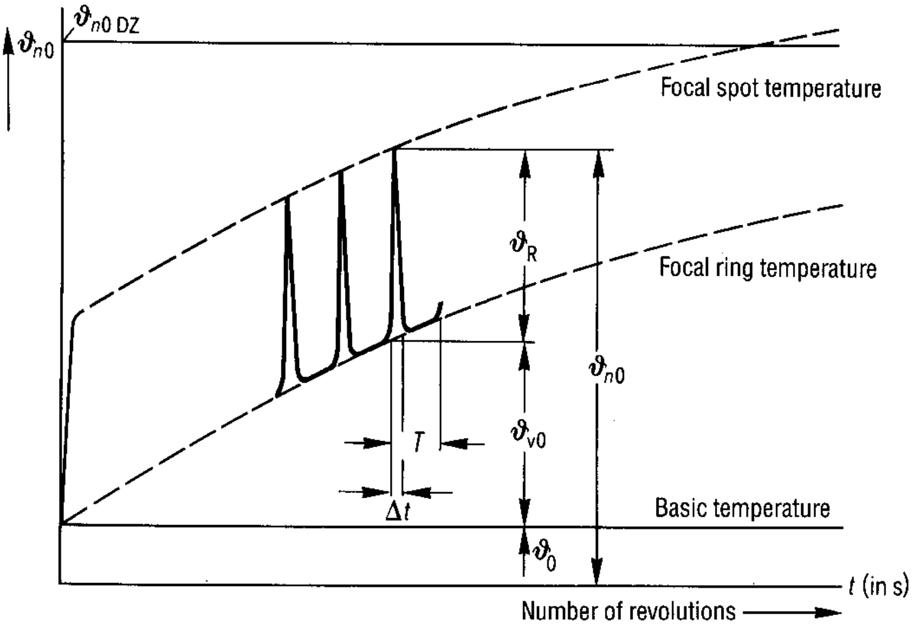


Fig. 7.22 Temperature increase in the focal spot on the rotating anode

Here k is a correction factor which takes into account the effects of the anode thickness, the thermal radiation at high temperatures and the heat diffusion in the radial direction. The result of these calculations is shown in Fig. 7.22.

From the calculations of the temperature distribution beneath the focal ring as a function of time and depth, which is given by

$$\vartheta_{z,t} = \frac{1}{2}\vartheta_R \sqrt{\frac{\Delta t}{t}}\, e^{-\frac{z^2 \varrho c}{4\lambda t}} \tag{7.10}$$

z Depth of anode

and is shown as an example in Figure 7.23, it follows that the temperature in the focal ring is virtually levelled out before each subsequent passage through the electron beam. It is, however, equally clear that very high temperature gradients occur, which, as already described, lead to the destruction of the anode surface. (Since in particular the mechanical stresses which arise in the direction of the circumference can lead to cracking of the disk, this is prevented by placing slits in the radial direction, Fig. 7.24).

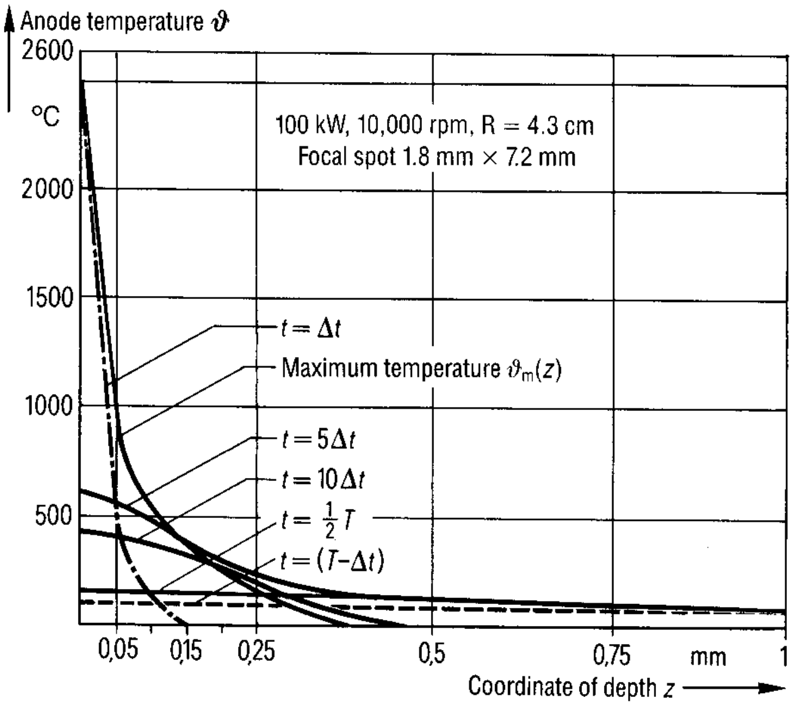


Fig. 7.23
Temperature of the anode beneath the focal ring after at most one revolution T

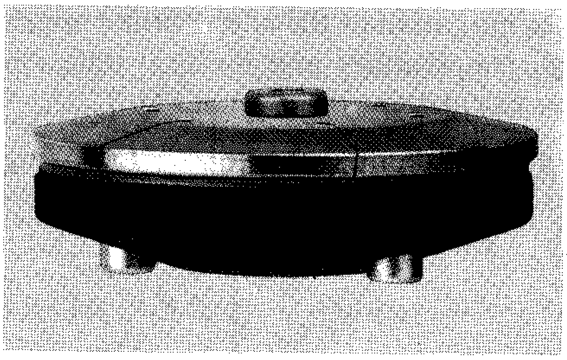
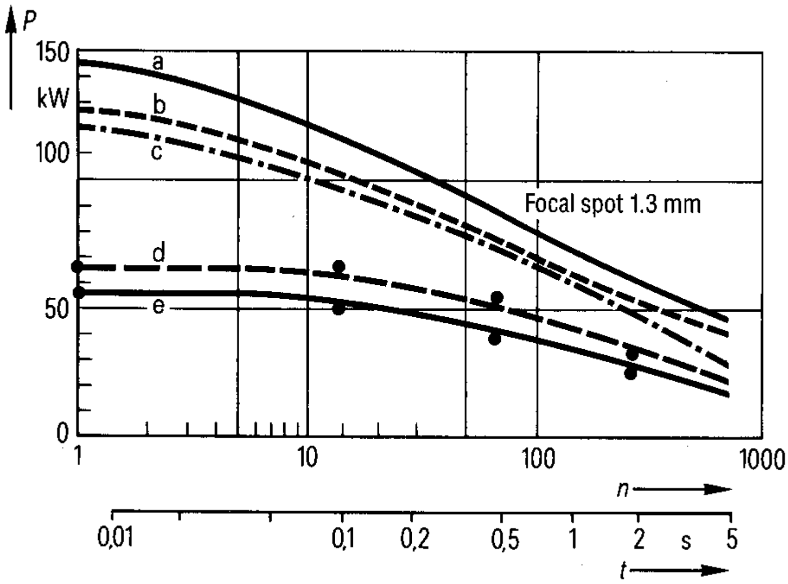


Fig. 7.24
Stress relieved CALOREX anode in which potential mechanical stresses are avoided by means of radial slits

An upper temperature limit ($\theta_{n_0 z}$) in the focal spot is reached when, as a consequence of the ionization of the evaporating metal, there is an arc discharge between cathode and anode. For reasons of safety during operation, a value for the admissible focal spot temperature is set which is lower by an amount



a Metal-graphite anode (2 mm metal and 15 mm graphite and CALOREX anode design) at 150 Hz and 6 pulse operation

b Graphite anode with 0.1 mm rhenium metal layer at 150 Hz and 6 pulse operation

c RTM anode at 150 Hz and 6 pulse operation

d RTM anode at 150 Hz, but 4 pulse operation

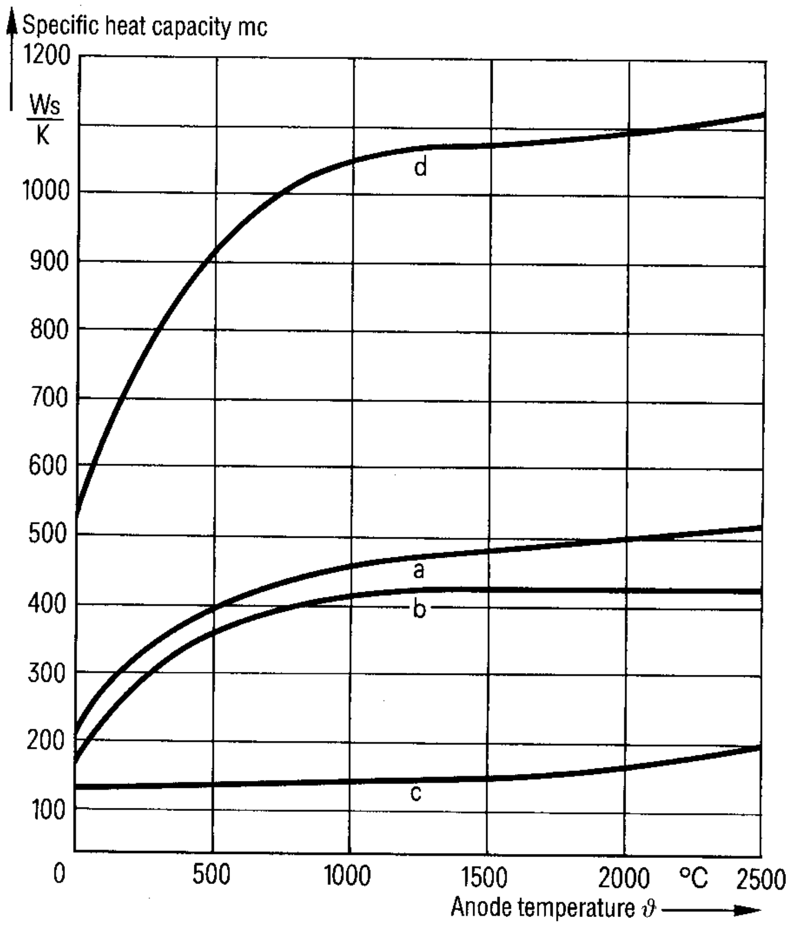
e RTM anode at 50 Hz, but 6 pulse operation

Fig. 7.25
Rating curves of rotating anode x-ray tubes for constant focal spot temperature of 2500 °C and constant maximum temperature in the boundary layer between metal and graphite in compound anodes

$\Delta\theta_s$. Thus, by combining the equations (7.4 to 7.9) and solving for the power, one obtains

$$P=\frac{\pi(\vartheta_{n_0\,z}-\Delta\vartheta_s-\vartheta_0)\sqrt{\lambda\varrho c}\cdot l\cdot\sqrt{fR\delta}}{1+k\sqrt{t\cdot f\cdot\dfrac{\delta}{\pi\cdot R}}}. \tag{7.11}$$

In any particular case a rating curve is valid only for an anode with a known basic temperature. The basic temperature of the anode depends on the preceding loads and interval periods.



a Metal-graphite anode (2 mm metal and 15 mm graphite) and CALOREX anode design
b Graphite anode with 0.1 mm rhenium metal layer
c RTM anode
d RTM anode with 33 mm thick graphite disk as a CALOREX anode for the Opti 151 CT x-ray tube used in computed tomography

Fig. 7.26
Heat capacity as a function of the temperature for four different types of anode

From the heat capacity of the anode and the summed power, on the one hand (Fig. 7.26), and the cooling curve determined by the power radiated away

$$P = A_A \sigma_0 \varepsilon(T)(T_A^4 - T_0^4) \tag{7.12}$$

A_A Surface area of anode
σ_0 Constant of radiation
$\varepsilon(T)$ Specific emission capacity
T_A Anode temperature
T_0 Surrounding temperature

on the other hand, the basic temperature can be found in each case.

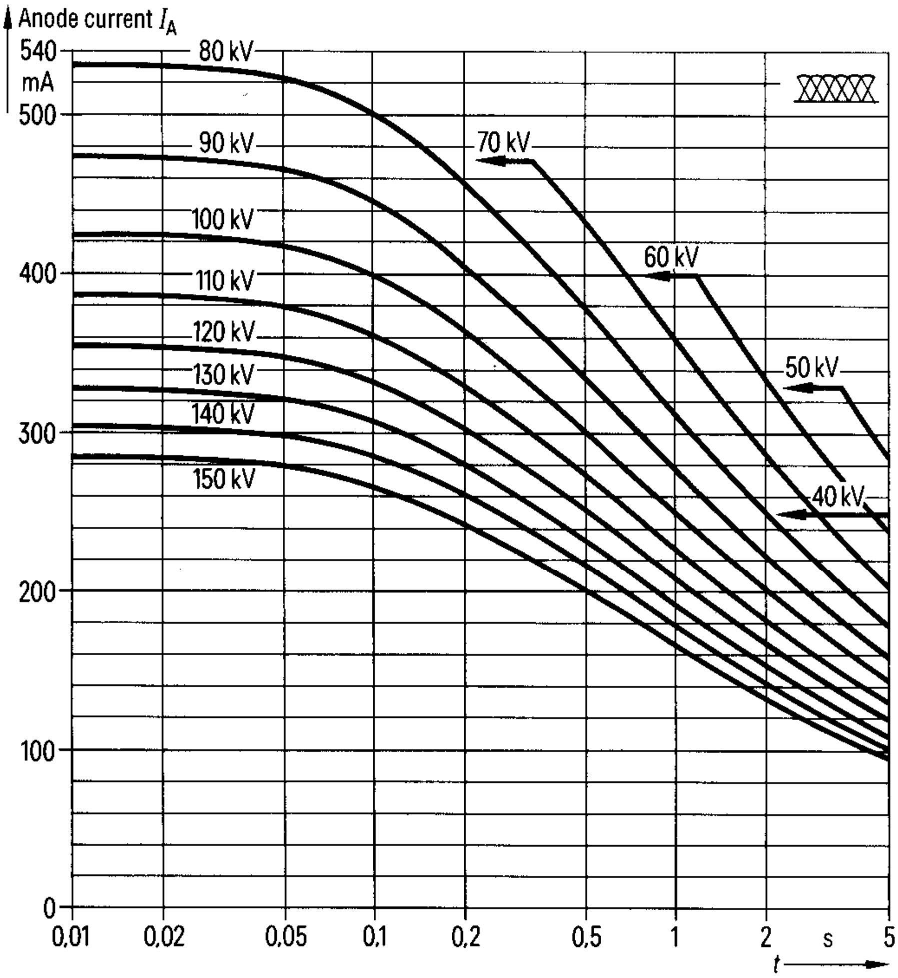
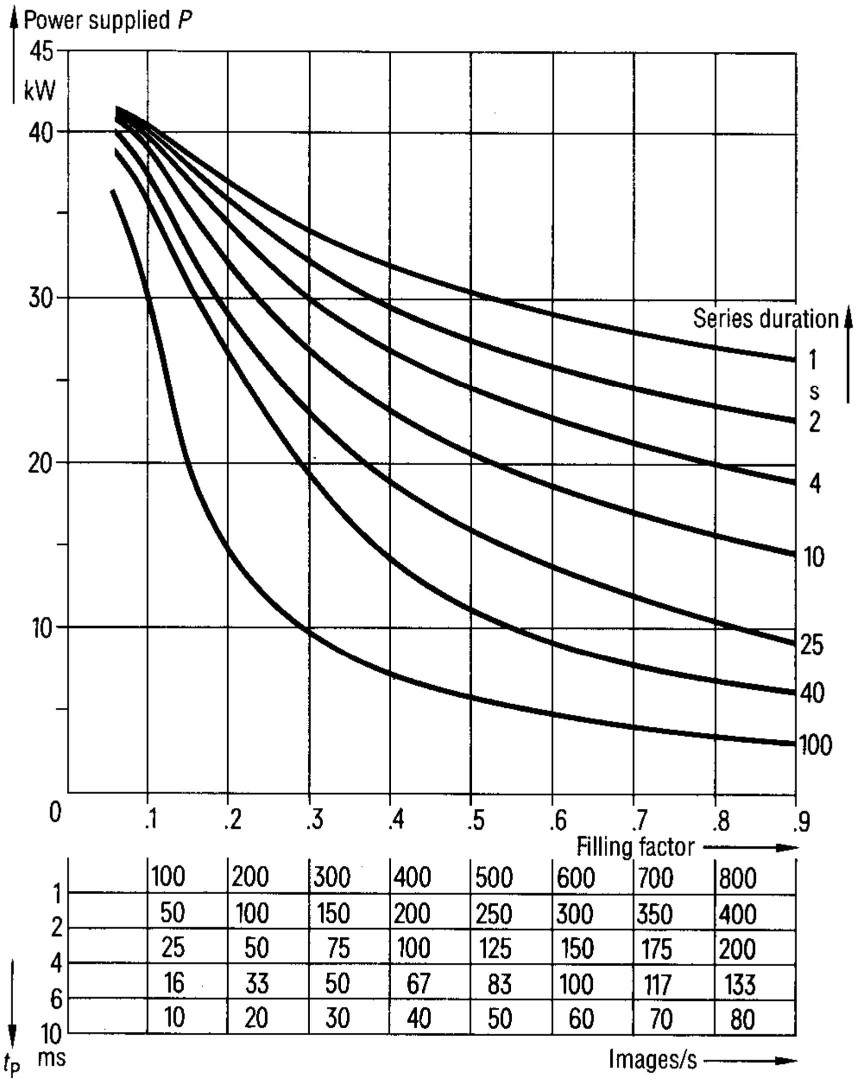


Fig. 7.27
Rating curves for a focal spot 0.6 mm, 40 kW, 150 Hz. The anode current as a function of the load period is valid for an anode preheated with 300 W with the anode voltage as a parameter. The sharp bends in the curves at low anode voltages are due to the limits on the emission of the cathode

For practical purposes, x-ray tube rating charts usually give the permitted anode currents as a function of the load period with the voltage as a parameter.

The sharp bends in the curves for low voltages are due to the limited emission capacity of the cathode. In these curves a basic thermal state (e.g. 300 W) is assumed. This is established by experience for normal operation of the x-ray tube. If the tube has previously had a higher load, the exposure power has to be reduced or a pause has to be made before the next exposure.

The thermal state can be monitored by means of direct measurement of the anode temperature, e.g. using the LOADIX system [7.8].



t_p ms	.1	.2	.3	.4	.5	.6	.7	.8
1	100	200	300	400	500	600	700	800
2	50	100	150	200	250	300	350	400
4	25	50	75	100	125	150	175	200
6	16	33	50	67	83	100	117	133
10	10	20	30	40	50	60	70	80

Fig. 7.28
Serial rating curves for a focal spot 0.6 mm, 40 kW, 150 Hz, with the series duration as a parameter, as a function of the filling factor, which corresponds to the ratio of pulse length to pulse interval.

Modern x-ray installations offer an indirect, but very reliable method using a tube load calculator. This system, apart from monitoring the current thermal state of the anode, checks whether for the given exposure settings there is a danger of overloading.

In normal radiography, it is the permitted focal spot temperature limit which usually determines the power limit for the exposure. In serial exposure operation or in pulsed cineradiography, in which a large number of exposures is made quickly one after another over a long period, one has in addition a power limitation due to the permitted basic anode temperature. The permitted load values as a function of series duration, number of exposures per second and the duration of a single exposure can be taken from the relevant diagrams (Fig. 7.28). It also applies here that at the beginning of a series, the thermal reference power of the anode for which the diagram was determined must not be exceeded.