Chapter 2
The Production and Properties of X Rays

Radiation Dosimetry I

Text: H.E Johns and J.R. Cunningham, The physics of radiology, 4th ed.

http://www.utoledo.edu/med/depts/radther

X-ray tube design

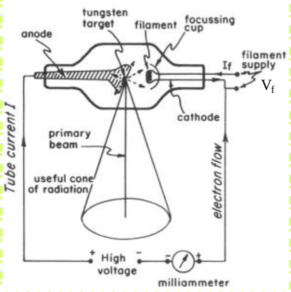


Figure 2-1 (a). Schematic diagram of x-ray tube and circuit

- Filament is heated, releasing electrons via thermionic emission (V_f ~ 10V, I_f ~ 4A, resulting in T>2000°C)
- X rays are produced by high-speed electrons bombarding the target
- Typically < 1% of energy is converted to x rays; the rest is heat

X-ray tube current

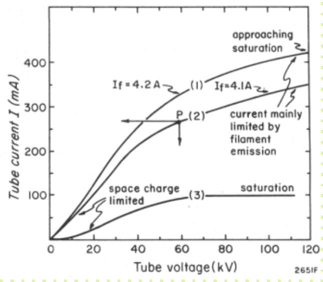


Figure 2-1 (b). Tube current as function of tube voltage. Curve 3: tube operating at a lower current

- Electron cloud near the filament creates space charge region, opposing the release of additional electrons
- Increase in tube voltage increases tube current; limited by filament emission
- High filament currents and tube voltage of 40 to 140kV must be used

X-ray tube: power source

- The source of electrical power is usually ac (easier to transmit through power lines)
- X-ray tubes are designed to operate at a single polarity: positive anode, negative cathode
- Need to manipulate available power source (suppress or rectify wrong polarity)
- The highest x-ray production efficiency can be achieved at a constant potential

Alternating currents and voltages

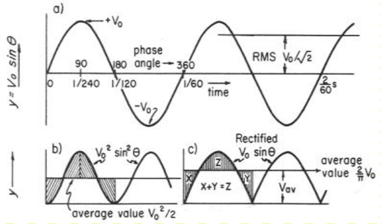


Figure 2-3. (a) Diagram to illustrate the variations with time (or phase angle) of an alternating voltage at 60 Hz. (b) Diagram to show that the RMS value is $V_0/\sqrt{2}$. (c) Diagram to illustrate that the average value of a sinusoidal rectified voltage (or current) is $2/\pi$ times the peak value.

- Phase changes from 0 to 360° during the 1 cycle time of 1/60 s
- Negative wave is suppressed or rectified
- Averaging: $V_{av} = \frac{2}{\pi} V_0$ or $V_{rms} = \frac{1}{\sqrt{2}} V_0$

Alternating currents and voltages

Current flows in one direction: series of pulses

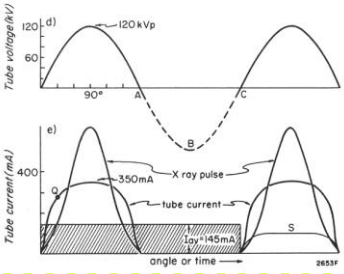


Figure 2.3 (d) High voltage from secondary of transformer with peak value of 120 kV. The inverse part of the cycle is ABC. (e) Tube current for the circuit of Figure 2-2 when the x ray tube has the characteristics of curve 2 of Figure 2-1b and the tube voltage is given by Figure 2-3d. The intensity of the resulting x ray pulse calculated assuming x ray production is proportional to IV^2 is also given. Curve S is the current pulse using the saturation curve 3 of Figure 2-1b.

Rectification

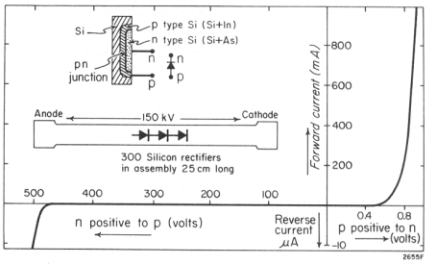
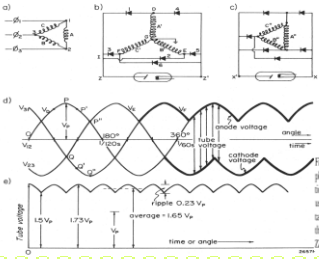


Figure 2-4. Schematic diagram of a p,n silicon rectifier. The operating characteristics are for the MR2272, a typical silicon rectifier. Note that the voltage and current scales are different for the forward and reverse directions. In the insert is shown a Machlett rectifier, which consists of some 300 rectifiers in series in a tube 25 cm long and capable of withstanding an inverse voltage of 150 kV.

Three phase units

- Need to increase pulse repetition rate to deliver high x ray flux in a short period of time
- Three phase units: voltage between any pair of 3 wires



Tube potential is almost constant, with a "ripple"

Figure 2-6. Diagram to illustrate 3 phase power and its use in x ray generators. (a) Three phase power line 1,2,3 connected to three primary windings A, B, C in a delta configuration. (b) Connections of the secondaries A′, B′, C′ in Y configuration to an x ray tube using 6 rectifiers giving a "6 pulse" system. (c) Secondaries A″, B″, C″, connected in a delta configuration to also give a 6 pulse system. (d) Wave forms for either V_{12}, V_{23}, V_{31}, or the voltages on D, E, and F, relative to ground. (e) Tube voltage, that is the voltage across ZZ′, as a function of time.

Example 1

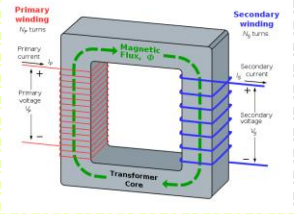
- Which type of x-ray generator produces the highest effective tube voltage, assuming the peak voltage is applied across the tube?

A. One-phase
B. Three-phase
[✓ C.] Constant potential
D. The effective voltage is the same for all types above.

In C - effective voltage = peak voltage

Example 2

Ratio of the turns in a transformer is N. Given an input RMS (primary) voltage, what is the peak output (secondary) voltage?



Faraday's law:

$$V_S = N_S \frac{d\Phi}{dt}; \quad V_P = N_P \frac{d\Phi}{dt}$$

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} = N$$

$$V_S = N\sqrt{2} \cdot V_{P\,RMS}$$

$$V_{RMS} = V_0 / \sqrt{2}$$

Diagnostic x ray tubes

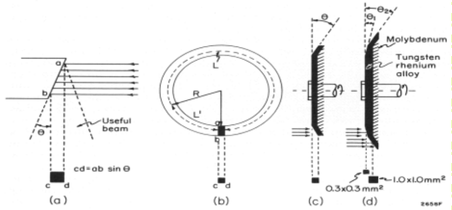


Figure 2-7. Diagrams illustrating anode construction and focal spots. (a) Line focus fixed anode. (b) Line focus rotating anode, viewed from the end. (c) Line focus rotating anode viewed from the side. (d) Alternative arrangement of rotating anode using two separate "tracks" at different angles as in the Siemens "Biangulix" series.

- The objective is to deliver x ray beam from a point source in a very short time
- To overcome heating need to spread electrons over some area that appears as a point

Example 3

- What energy (kJ) is imparted to a rotating anode (0.25 kg) during a 2 s exposure that produced a temperature of 2500°C. Specific heat of tungsten is 0.035 kcal/kg°C, and 1 cal = 4.186 J

A. 17.9
B. 45.7
C. 87.5
[✓ D.] 91.5
E. 182.9

Duration of exposure is irrelevant

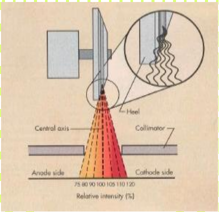
$$E = cm\Delta T =$$

$$0.035 \cdot 4.186 \times 10^3 \cdot 0.25 \cdot 2500 =$$

$$91.5 \times 10^3 = 91.5\ \text{kJ}$$

Diagnostic x ray tubes

Image from
http://www.slideshare.net/jdtomines/x-ray-tube



Intensity profile

- X-rays that are emitted from the target travel through different thickness of cathode material
- *Heel effect*: radiation intensity toward the cathode side of the x-ray tube is higher than on the anode side
- Cathode is typically mounted over the thicker part of the patient to balance the amount of transmitted photons on the imager

Rating of diagnostic tubes

- Focal spot loading determines the maximum permissible exposure: there is a maximum power that can be tolerated before target starts melting ($T_{melting}$=3400^{o}C for tungsten)
- Anode cooling and housing cooling rates determine the number of exposures that may be given in a sequence

Rating of diagnostic tubes

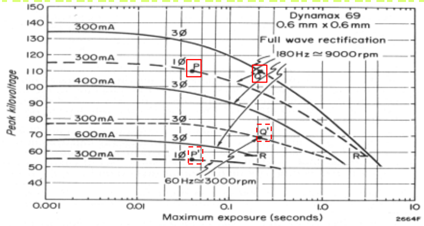
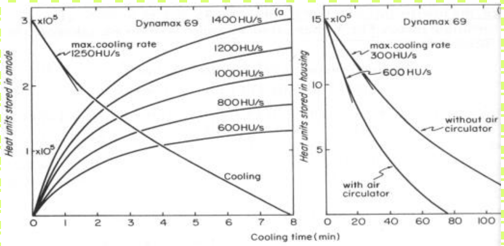


Figure 2-11. Curves giving the maximum kV$_p$ for a given exposure for a Machlett Dynamax 69 under a number of different excitation conditions. Focal spot 0.6 mm × 0.6 mm, full wave rectification. Data for single exposures.

- The combination of current and voltage must lie to the left of the appropriate curve
- The maximum duration of a single exposure depends on spot size, anode rotation speed, current, voltage, power supply type

Rating of diagnostic tubes



- Heat stored in the anode and its cooling rate limits the number of exposures given in a sequence
- Heat unit HU characterizes the energy deposited within the anode in a single exposure

X ray tubes for radiotherapy

- Mostly for superficial treatments
- No need for a small spot source
- The instantaneous energy input is small (about 1/10) but the average energy input is ~ 10 times greater compared with a diagnostic tube
- Due to much higher energy (>200keV) of electrons bombarding the target, there is a problem of secondary electrons emerging from the target
  - Solution: the target is placed in a "hood" - hollow tube with copper shielding intercepting the secondary electrons

X-ray spectra

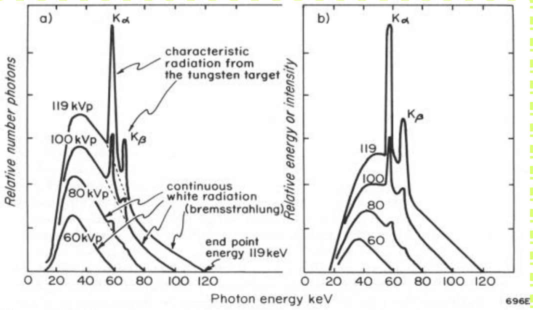
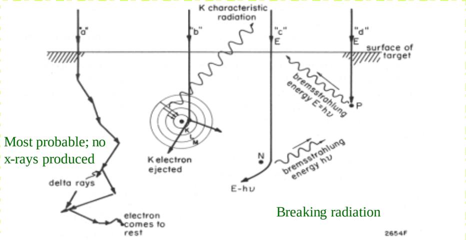


Figure 2-13. Observed spectra from a diagnostic x ray tube excited at 60, 80, 100, and 119 kV$_p$, due to Yaffe (Y1), added filter 2 mm Al.

Interactions of electrons with the target to give x rays



Most probable; no x-rays produced

Breaking radiation

Figure 2-14. Typical electron interactions with a target. (a) Electron suffers ionizational losses, giving rise to delta rays and eventually heat. (b) The electron ejects a K electron, giving rise to characteristic radiation. (c) Collision between an electron of energy E and a nucleus, leading to bremsstrahlung of energy hν. The electron recedes from the "collision" with energy E − hν. (d) Rare collision when the electron is completely stopped in one collision, giving rise to a photon of energy E = hν.

Characteristic radiation

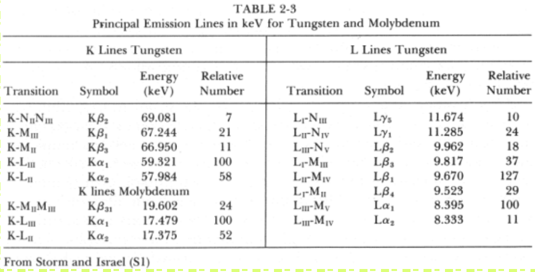


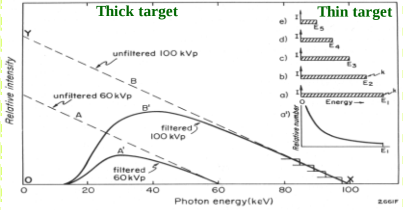
TABLE 2-3
Principal Emission Lines in keV for Tungsten and Molybdenum

K Lines Tungsten				L Lines Tungsten			
Transition	Symbol	Energy (keV)	Relative Number	Transition	Symbol	Energy (keV)	Relative Number
$K\text{-}N_{II}N_{III}$	$K\beta_2$	69.081	7	$L_I\text{-}N_{III}$	$L\gamma_5$	11.674	10
$K\text{-}M_{III}$	$K\beta_1$	67.244	21	$L_{II}\text{-}N_{IV}$	$L\gamma_1$	11.285	24
$K\text{-}M_{II}$	$K\beta_3$	66.950	11	$L_{III}\text{-}N_V$	$L\beta_2$	9.962	18
$K\text{-}L_{III}$	$K\alpha_1$	59.321	100	$L_I\text{-}M_{III}$	$L\beta_3$	9.817	37
$K\text{-}L_{II}$	$K\alpha_2$	57.984	58	$L_{II}\text{-}M_{IV}$	$L\beta_1$	9.670	127
K lines Molybdenum				$L_I\text{-}M_{II}$	$L\beta_4$	9.523	29
$K\text{-}M_{II}M_{III}$	$K\beta_{31}$	19.602	24	$L_{III}\text{-}M_V$	$L\alpha_1$	8.395	100
$K\text{-}L_{III}$	$K\alpha_1$	17.479	100	$L_{III}\text{-}M_{IV}$	$L\alpha_2$	8.333	11
$K\text{-}L_{II}$	$K\alpha_2$	17.375	52				

From Storm and Israel (S1)

- Different transitions have different probabilities, according to quantum mechanics selection rules (some transitions are forbidden)

Bremsstrahlung interaction



Thick target

Thin target

Figure 2-15. Relative energy or intensity I, in each photon energy interval produced when a beam of monoenergetic electrons of energy E_1 bombard a thin target. The distribution a' is the data of a converted to a number distribution. Curves b, c, d, and e are thin target intensity spectra similar to a but for electron energies of E_2, E_3, E_4, and E_5. The main diagram shows *thick target* spectra (dotted lines A and B) produced by the superposition of many thin target spectra when the target is bombarded with 60 and 100 keV electrons. The solid curves A' and B' were obtained from A and B by taking into account the attenuation of 2 mm A1.

- Thin target approximation: one collision per electron
- Thick target approximations: $I(E) = C\,Z\,(E_{max} - E)$

Example 4

- The energy levels of K, L, and M shells in tungsten are -69.5, -11.0, and -2.5 keV. What photon energies will be present in its characteristic X-ray spectrum?

[✓ A.] 67.0, 58.5, 8.5 keV

B. 80.5, 72.0, 13.5 keV

C. 69.5, 1 1 .O, 2.5 keV

D. Continuous spectrum from 2.5 to 69.5 keV

E. Continuous spectrum below 2.5 keV

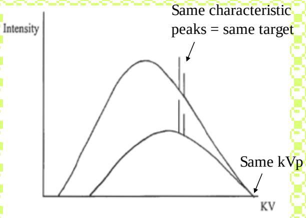
Photon energies are equal to the differences between corresponding energy levels

Example 5

- In the graph below, the two X-ray spectra shown have the same

1. Filtration
2. Target material
3. HVL
4. KVp

A. 1,2,3,4
B. 1,3
[✓ C.] 2,4
D. 3,4
E. 4 only



Same characteristic peaks = same target

Same kVp

Different intensity – different filtration and HVL

Example 6

- A target material has the following binding energies: K=30 keV, L=4 keV, M=0.7 keV. If 40.0 keV electrons are fired at the target, what kind of x-rays can have the following energies?
- 6-1: 34 keV
- 6-2: 26 keV
- 6-3: 40.7 keV

A. Characteristic only
B. Bremsstrahlung only
C. Both A and B
D. Neither A nor B

Answers:
- 6-1: B
- 6-2: C
- 6-3: D