X-rays

Ouch!
X-rays

- X-rays are produced when electrons are accelerated and collide with a target
  - Bremsstrahlung x-rays
  - Characteristic x-rays

- X-rays are sometimes characterized by the generating voltage
  - 0.1-20 kV: soft x-rays
  - 20-120 kV: diagnostic x-rays
  - 120-300 kV: orthovoltage x-rays
  - 300 kV - 1 MV: intermediate energy x-rays
  - > 1 MV: megavoltage x-rays
Bremsstrahlung x-rays occur when electrons are (de)accelerated in the Coulomb field of a nucleus.
Bremsstrahlung
Bremsstrahlung

- The power radiated from an accelerating charge is given by Larmor's equation

\[ P = \frac{2}{3} \frac{e^2 a^2}{c^3} \]

- In the case of an electron in the Coulomb field of a nucleus

\[ a = \frac{F}{m} = k \frac{Ze^2}{r^2 m} \sim Z \]
Bremsstrahlung

- The probability of bremsstrahlung goes as $Z^2$, hence high $Z$ targets are more effective than low $Z$.
- The energy of the x-rays varies from zero to the maximum kinetic energy of the electron (x-ray tube kVp).
- The energy spectrum from a thick target goes as $1/E$ but inherent (1mm Al eq) plus additional (few mm Al) filtration removes the lower energy x-rays.
  - Here I am referring to diagnostic x-rays.
The unfiltered energy spectrum is approximately given by Kramer’s law which was an early application of quantum mechanics

$$I(E_\gamma) = KZ(T_e - E_\gamma)$$
Bremsstrahlung

The diagram illustrates the relative intensity per energy interval for various photon energies. It shows the distribution of characteristic radiation and the influence of different excitation voltages (65 kv, 100 kv, 150 kv, 200 kv) on the intensity of the radiation. The K lines of tungsten and the unfiltered characteristic radiation are also indicated.
After excitation, ions with a vacancy in their inner shell can de-excite:

- Radiatively through x-ray fluorescence
- Non-radiatively through the emission of Auger electrons
Characteristic X-rays

- Thus an x-ray spectrum will also show characteristic x-rays arising from L to K and M to K transitions after ionization of a K electron.
  - Usually transitions to higher shells absorbed by the filtration or are not x-rays.
Characteristic X-rays

- The probability of K shell fluorescence increases with Z

Figure 3.22: Fluorescence yield for the K shell versus atomic number as predicted by the polynomial equations of Michette and Laberrigue-Frolov and Radvanyi (LFR) compared to the data of Storm and Israel.
**Characteristic X-rays**

<table>
<thead>
<tr>
<th>Electron Shell</th>
<th>Tungsten</th>
<th>Molybdenum</th>
<th>Rhodium</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>69.5</td>
<td>20.0</td>
<td>23.2</td>
</tr>
<tr>
<td>L</td>
<td>12.1/11.5/10.2</td>
<td>2.8/2.6/2.5</td>
<td>3.4/3.1/3.0</td>
</tr>
<tr>
<td>M</td>
<td>2.8–1.9</td>
<td>0.5–0.4</td>
<td>0.6–0.2</td>
</tr>
</tbody>
</table>

**K-shell Characteristic X-ray Energies (keV)**

<table>
<thead>
<tr>
<th>Shell transition</th>
<th>Tungsten</th>
<th>Molybdenum</th>
<th>Rhodium</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\alpha 1}$</td>
<td>59.32</td>
<td>17.48</td>
<td>20.22</td>
</tr>
<tr>
<td>$K_{\alpha 2}$</td>
<td>57.98</td>
<td>17.37</td>
<td>20.07</td>
</tr>
<tr>
<td>$K_{\beta 1}$</td>
<td>67.24</td>
<td>19.61</td>
<td>22.72</td>
</tr>
</tbody>
</table>

*Only prominent transitions listed.*
Characteristic X-rays

- Sometimes the characteristic x-rays are emphasized using the same material for target and filter
  - Characteristic x-rays from molybdenum are effective in maximizing contrast in mammography
Characteristic X-rays

Mo target, filter, and result

![Graph of 30 kVp unfiltered Bremstrahlung spectrum - moly target](image)

![Graph of Mass attenuation coefficient - Molybdenum](image)

![Graph of 30 kVp filtered Bremstrahlung spectrum - moly target](image)
Directionality

- For MeV electrons, bremsstrahlung x-rays are preferentially emitted in the electron’s direction.
- For keV electrons, bremsstrahlung x-rays are emitted at larger angles.
- Characteristic x-rays are emitted isotropically since there is no angular correlation between the incident electron that causes the ionization and the fluorescent photon.
A simplified x-ray tube (Coolidge type) shows the idea behind most x-ray tubes today.
In addition to bremsstrahlung and characteristic x-ray production, electrons also lose energy through collisions.

- Collision losses dominate in this energy region:
  \[
  \frac{\text{radiation loss}}{\text{collision loss}} \approx \frac{EZ}{820} (E \text{ in MeV})
  \]

- For 100 keV electrons in W:
  \[
  \frac{\text{radiation loss}}{\text{collision loss}} \approx \frac{0.1 \cdot 74}{820} = 0.009
  \]

- Thus >99% of the electron energy goes into heating the target rather than x-rays.
- Removing heat from the anode in a vacuum is an issue.
Efficiency of x-ray production depends on the tube voltage and the target material.

- W (Z=74) in this example

\[ P_{\text{deposited}} = VI \]

\[ P_{\text{radiated}} = 0.9 \times 10^{-9} Z V^2 I \]

Efficiency \( \varepsilon = \frac{P_{\text{radiated}}}{P_{\text{deposited}}} = 0.9 \times 10^{-9} Z V \)

<table>
<thead>
<tr>
<th>kVp (V)</th>
<th>Heat (%)</th>
<th>X-rays (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>99.7</td>
<td>0.3</td>
</tr>
<tr>
<td>200</td>
<td>99</td>
<td>1</td>
</tr>
<tr>
<td>6000</td>
<td>65</td>
<td>35</td>
</tr>
</tbody>
</table>
X-ray Tube

X-ray tubes
X-ray Tube

More detail
X-ray Tube

- Housing for shielding (Pb) and cooling (oil)
X-ray Tube

More detail
The main parts of the x-ray tube are

- **Cathode/filament**
  - Typical electron current is 0.1-1.0 A for short exposures (< 100 ms)
- **Anode/target**
- **Glass/metal envelope**
- **Accelerating voltage**
  - Typical voltage is 20-150 kVp
Cathode

- Cathode consists of
  - Low R tungsten wire for thermionic emission
    - Tungsten has a high melting point (3370°C) and minimum deposit on the glass tube
    - Tube current is controlled by varying the filament current which is a few amps
  - A focusing cup
    - Uses electric field lines to focus the electrons

- Typically there are two filaments
  - Long one: higher current, lower resolution
    - Large focal spot
  - Short one: lower current, higher resolution
    - Small focal spot
Cathode

 ➢ Dual focus filament is common
Anode

- Usually made of tungsten in copper because of high Z and high melting point
  - Molybdenum and rhodium used for soft tissue imaging
- Large rotating surface for heat distribution and radiative heat loss
  - Rotation of 3k-10k revolutions/minute
  - Resides in a vacuum (~10^-6 torr)
  - Thermally decoupled from motor to avoid overheating of the shaft
- Target is at an tilted angle with respect to axis
  - Bremsstrahlung is emitted at ~ right angles for low energy electrons
  - Determines focal spot size
Anode
Anode

- Tungsten-rhenium alloy
- Graphite
- Molybdenum
Anode

- The heating of the anode limits the voltage, current, and exposure time
- An exposure rating chart gives these limits
Anode

- Power = \( V \times I \) (watts)
- Energy = Power \times \text{time} = V \times I \times s \text{ (joules)}
- HU (Heating Unit) \sim J

- Damaged anodes
Anode

- The angle determines the projected focal spot
  - The smaller the angle the better the resolution
  - Typically 7-20 degrees
X-rays

- The energy of the photons depends on the electron energy (kVp) and the target atomic number Z.
- The number of photons depends on the electron energy (kVp), Z, and the beam current (mA).
  - A typical number / area is $\sim 10^{13} / m^2$.
  - About 1% will hit the film $\sim 10^{11} / m^2$.
  - Absorption and detection efficiency will further reduce this number.
Automatic Exposure Control

- AEC detectors can ionization chambers or solid-state detectors

Diagram:
- X Ray tube
- Collimator
- Beam
- Patient
- Table
- Grid
- Cassette
- Soft tissue
- Air
- Bone
Most modern x-rays machines are equipped with automatic exposure control also called a phototime.

The AEC sets the technical parameters of the machine (kV, mA, time, ...) in order to avoid repeated exposures.

AEC is used to keep the radiographic quality (film density) equal on all patients.

AEC detectors can be ionization chambers or solid state detectors.
To reduce the number of secondary scattered photons making it to the film, a grid between the patient and film is used.
Grid

Details

- Grid bars are usually lead whereas the grid openings are usually made of aluminum or carbon
- Grid thickness is typically 3 mm
- Grid ratio is H/W and 10/1 is typical
- Grid frequency of 60 lines/cm is typical
- B/W/H on the figure might be 0.045, 0.120, 1.20 in mm
- The Bucky factor is the entrance exposure with/without the grid while achieving the same film density – 4 is average
Accelerating Voltage

The potential difference between cathode and anode must be generated by 60 Hz 220V AC power

- High voltages are produced using a transformer

\[ \frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{N_p}{N_s} \]
Accelerating Voltage

Electrons are accelerated when the filament is at a negative potential with respect to the target.

- Diode circuits can be used to provide rectification (AC to DC voltage).
- Three phase power (6 pulse or 12 pulse) can be used to reduce ripple.
- Constant potential operation can be achieved by using constant potential (voltage regulations) or high frequency x-ray generators.
Half-wave Rectifier

Figure 10.24 Half-wave rectifier with resistive load.

Not very efficient
Full-wave Bridge Rectifier

This circuit allows the entire input waveform to be used.

Figure 10.28 Diode-bridge full-wave rectifier.
Accelerating Voltage

- Single phase single pulse
- Single phase 2-pulse
- Three phase 6-pulse
- Three phase 12-pulse

kV ripple (%)

- 100%
- 13%
- 4%

Line voltage

- 0.01 s
- 0.02 s