External Beam Delivery Systems

Argonne National Laboratory Course: 3DCRT for Technologists

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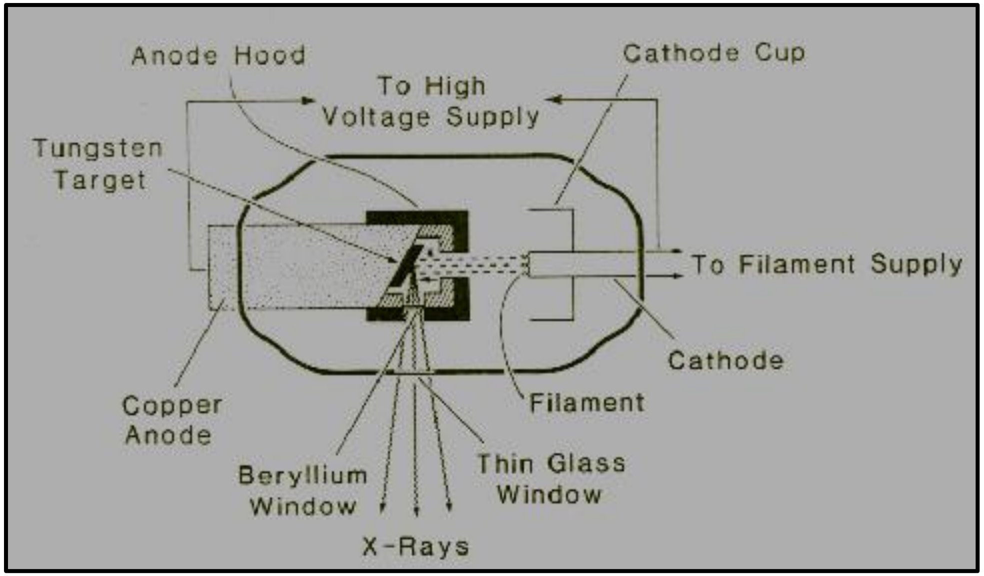
X-Ray Production

X rays, fundamentals, etc.

Production of X Rays

- **The X-Ray Tube**
  - Components (Figure 3.1 of Khan)
  - Glass tube – maintains vacuum necessary to minimize electron interactions outside of the target area
  - Cathode – contains filament and focusing cup
  - Anode – contains x-ray target



The X-Ray Tube

- The Cathode
  - Tungsten filament (high melting point – 3370 C)
  - Thermionic emission – electron production as a consequence of heating
  - Focusing cup – "directs" electrons to anode
  - Dual filaments (diagnostic tubes) – necessary to balance small focal spots and larger tube currents

The X-Ray Tube

- The Anode
  - Tungsten target
    - High melting point
    - High Z (74) – preferred since bremsstrahlung production α Z^2
  - Heat dissipation
    - Copper anode – heat conducted outside glass into oil / water / air
    - Rotating anode (diagnostic tubes) – larger dissipation area
  - Anode hood – copper and tungsten shields intercept stray electrons and x rays

Basic X-Ray Circuit

- Simplified diagram (Khan Figure 3.3)
- Consists of two parts:
  - High-voltage circuit – provides x-ray tube accelerating potential
  - Filament circuit – provides filament current

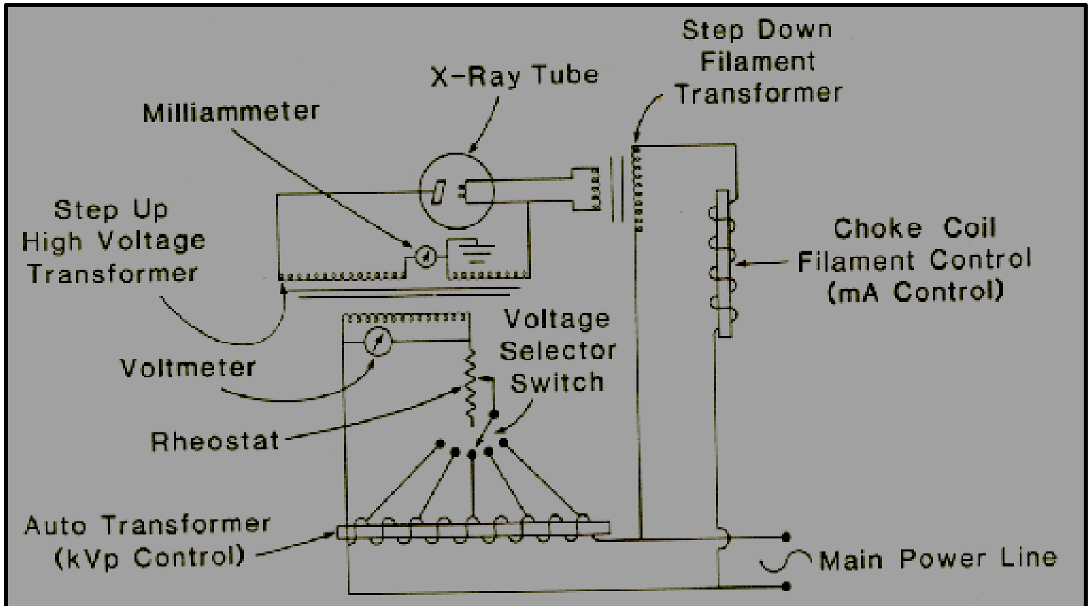
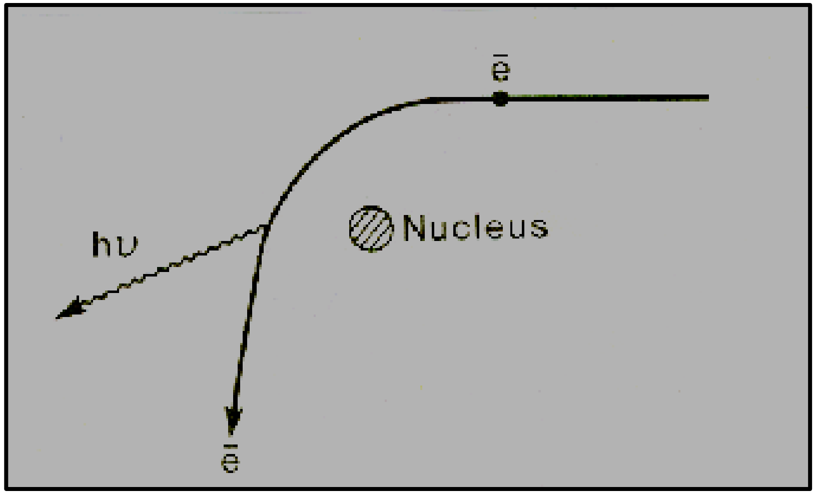


Figure 3.3. Simplified circuit diagram of a self-rectified x-ray unit.

X-Ray Production

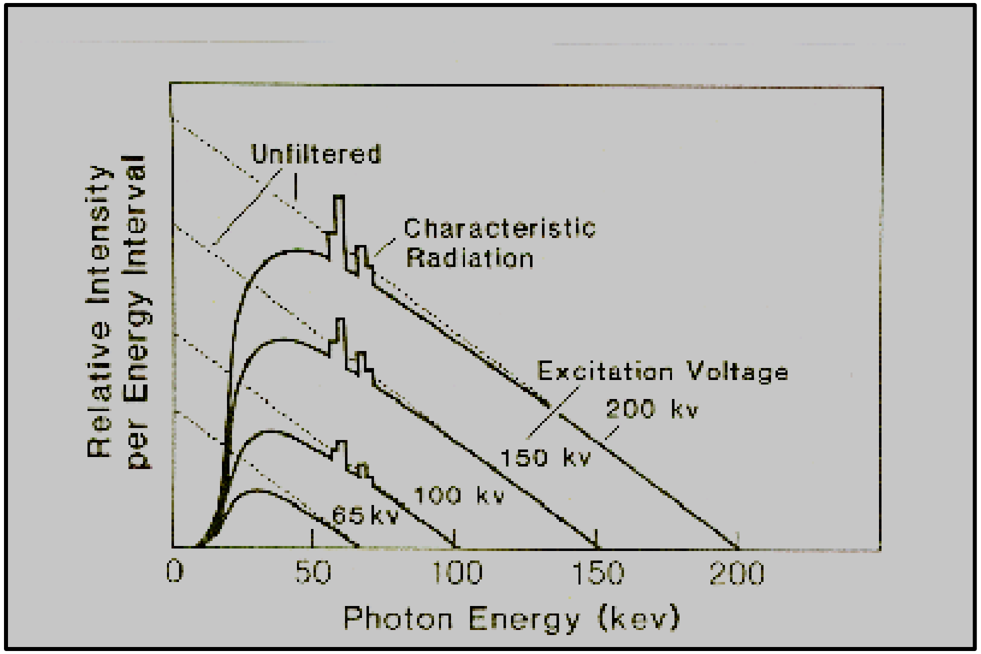
- Bremsstrahlung ("braking" radiation)
- Schematics (Khan Figure 3.6)
- Electromagnetic radiation emitted when an electron losses energy as a consequence of coulomb interaction with the nucleus of an atom



X-Ray Energy Spectrum

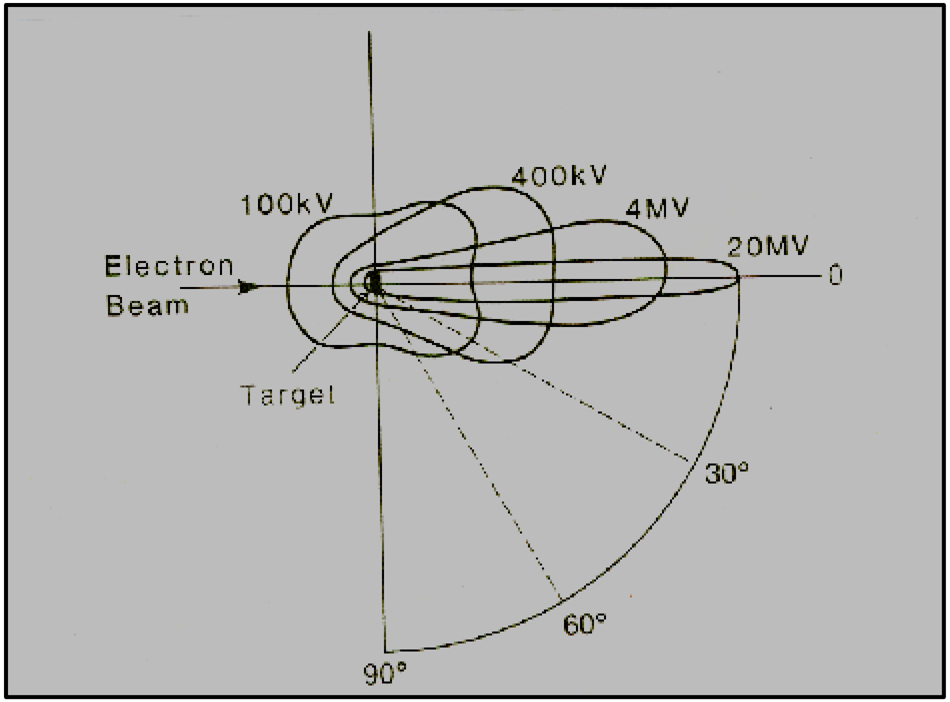
- The bremsstrahlung photon's energy is equal to the difference between electron's incident and final energies
  - This leads to an "energy spectrum" (the Kramer's spectrum):

$$I_E = K\,Z\,(E_m - E)$$



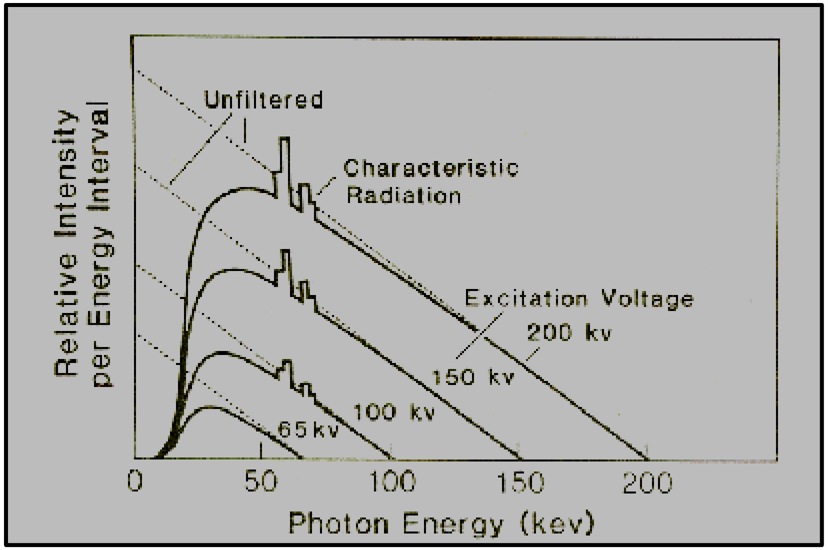
X-Ray Angular Distribution

- Angular distribution of x rays (Figure 3.8 of Khan)
  - Angular distribution becomes more “forward peaked” as the electron energy increases



X-Ray Spectrum

- X-Ray Spectrum (Figure 3.9 of Khan)
  - Composite of Kramer's spectrum and characteristic x rays
  - Filtration reduces lower-energy component
  - Rule of thumb is average energy ≈ 1/3 maximum energy
  - Half Value Layer (HVL) is a common descriptor



Clinical Radiation Generators

Treatment Unit	Kilovoltage Range	Half-Value Layer	Clinical Use
Grenz Ray	» 20 kVp	≈ 0.04-0.09 mm Al	Dermatological Use
Contact Therapy	40-50 kVp	≈ 1-2 mm Al	Few mm
Superficial Therapy	50-150 kVp	≈ 1-8 mm Al	Skin Lesions
Orthovoltage	150-500 kVp	≈ 1-4 mm Cu	Deep Therapy
Supervoltage	500-1000 kVp	≈ 10 mm Pb	Replaced by Co-60

Clinical Radiation Generators

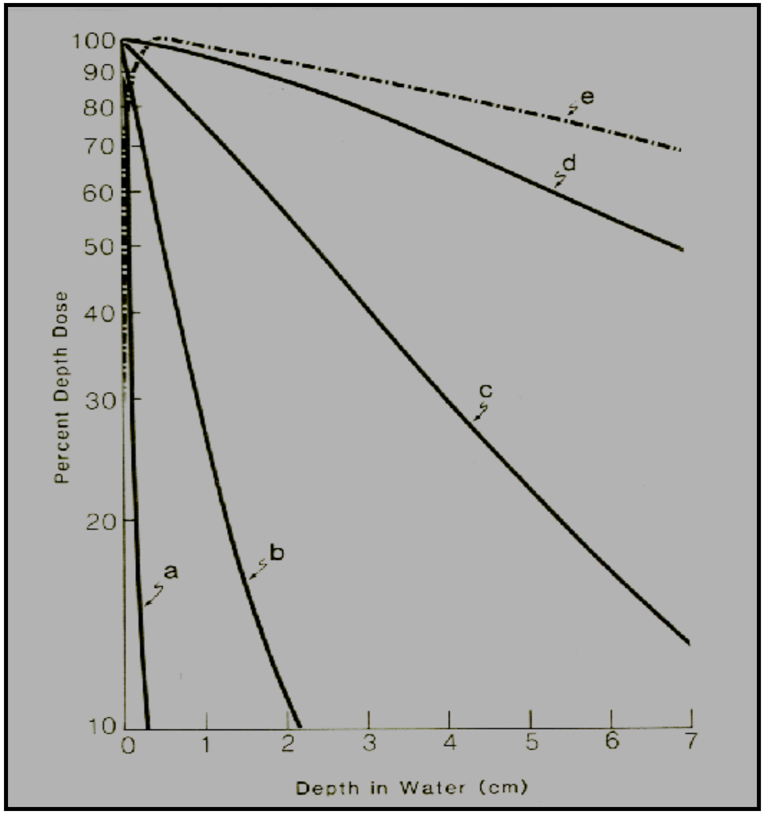


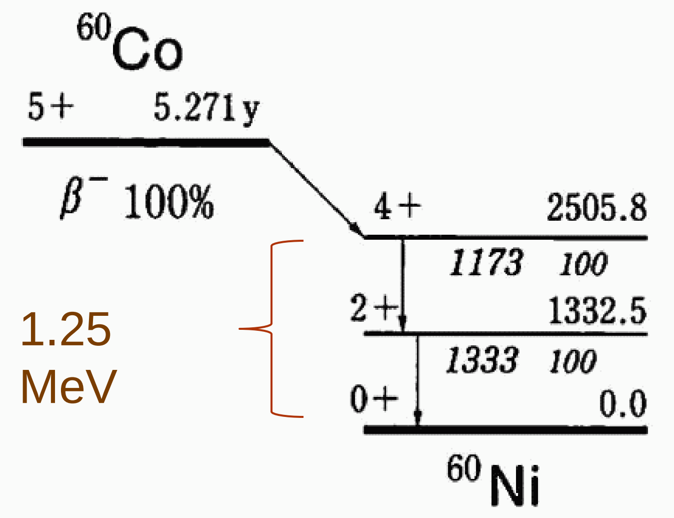
Figure 4.1. Depth dose curves in water or soft tissues for various quality beams. Line a: Grenz rays, HVL = 0.04 mm Al, field diameter ≈ 33 cm, SSD = 10 cm. Line b: Contact therapy, HVL = 1.5 mm Al, field diameter = 2.0 cm, SSD = 2 cm. Line c: Superficial therapy, HVL = 3.0 mm Al, field diameter = 3.6 cm, SSD = 20 cm. Line d: Orthovoltage, HVL = 2.0 mm Cu, field size = 10 × 10 cm, SSD = 50 cm. Line e: Cobalt-60 γ rays, field size = 10 × 10 cm, SSD = 80 cm. Plotted from data in Cohen M, Jones DEA, Green D, eds. Central axis depth dose data for use in radiotherapy. Br J Radiol 1978; suppl 11. The British Institute of Radiology, London.

Co-60 Teletherapy Units

Co-60 sources, teletherapy units – characteristics, operations, safety

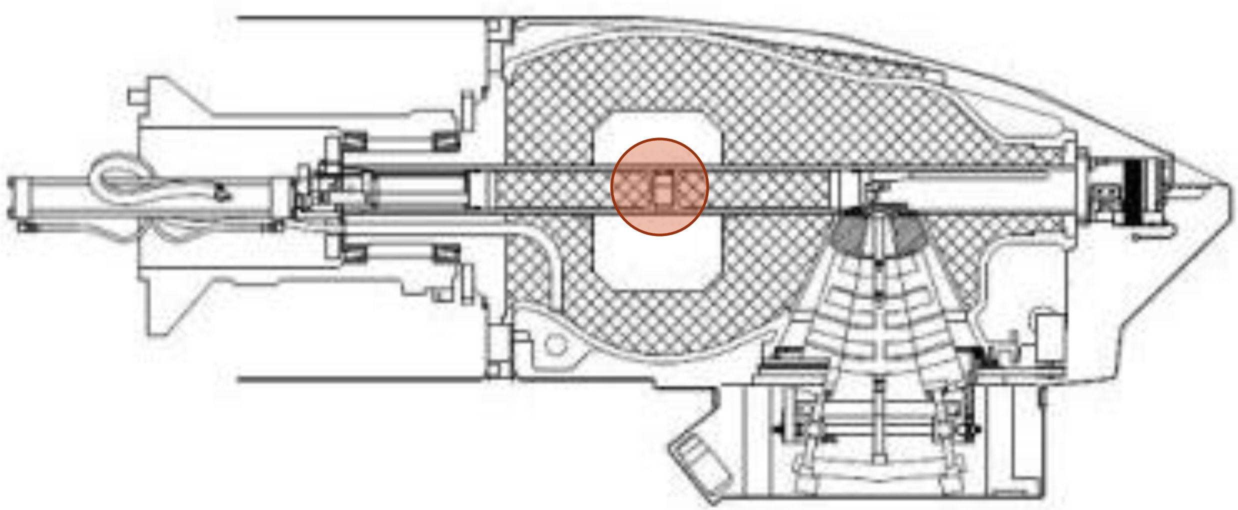
Co-60

- Co-60
  - Co-60 is most commonly used radionuclide for teletherapy because of its:
    - Superior specific activity per gram,
    - Its greater beam intensity per curie,
    - And its higher average photon energy.
  - A typical Co-60 source is 1 to 2 cm in diameter, and possesses an activity of about 5000 to 10000 Curies (370 TBq).
  - The source activity is limited by the physical size of the source.



Co-60 Teletherapy Units

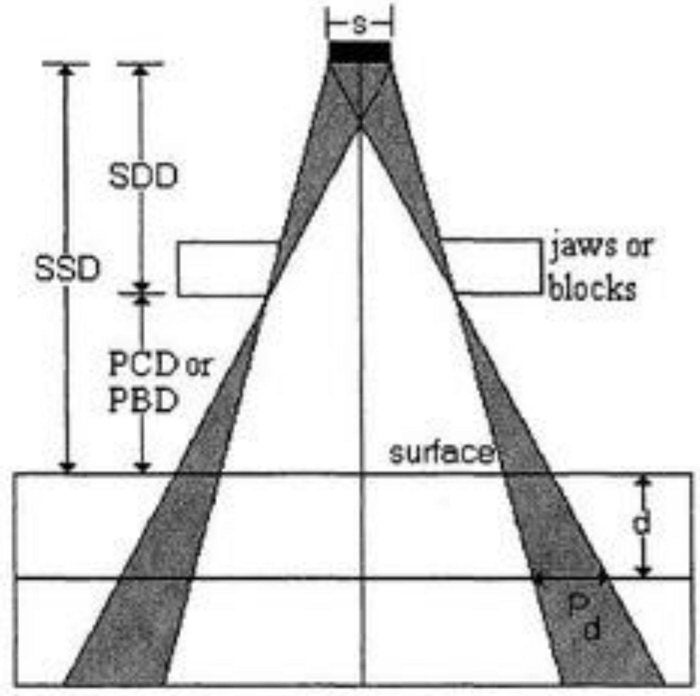
- Co-60 Source Exposure Mechanism
  - The Co-60 source is exposed using mechanical means (pneumatics mostly)
    - In its "off" position the source is shielded
    - In its "on" position the source is moved to an area of reduced shielding, where it is exposed
    - In its "on" position, force is applied such that it is retracted should power be lost



Co-60 Teletherapy Characteristics

- Co-60
  - The large size of the Co-60 source produces a significant geometric penumbra. If *s* is the source diameter and *SDD* is the distance from the source to the collimator (diaphragm), then at a source to skin distance, *SSD*, the width of the geometric penumbra, *P*, is given by:

$$P = s \times \left(SSD - SDD \middle/ SDD \right)$$



Co-60 Teletherapy Characteristics

- Timer Error
  - When the source is actuated and the timer begins counting, the source is moved to the "on" position; at the end of the set time, the source begins its motion back
  - Timer error is the difference in time between source exposure and source retraction
  - Timer error is measured by comparing multiple (n) short exposures (M_2) to a single longer exposure (M_1):

$$\frac{M_1}{t_1+\alpha}=\frac{M_2}{t_2+n\alpha}$$

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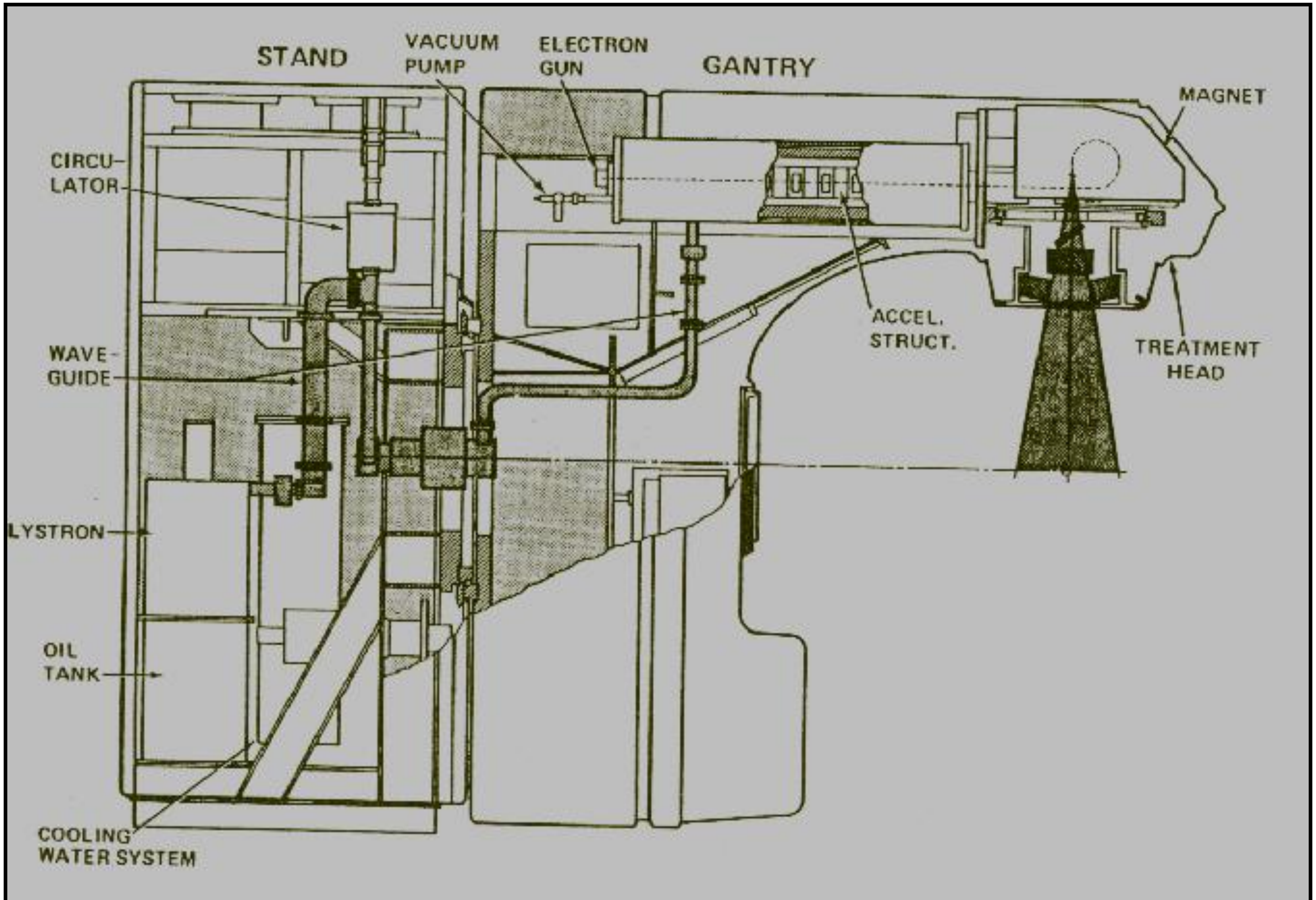
Co-60 Teletherapy Characteristics

- Beam characteristics
  - PDD at 10 cm depth, 10x10 cm field
    - 55.6%, Co-60, 80 SSD
    - 66.9%, 6 MV, 100 SSD
  - Penumbrae (80%-20%)
    - 1.2 cm Co-60 typical
    - 0.4 cm 6 MV typical
- Radiation Safety
  - Five-Year Inspection
    - Requirement in the USA by Nuclear Regulatory Commission
    - Source is replaced
    - Treatment Unit is refurbished
  - Emergency Procedures
    - Manual source insertion – yearly exercise
  - Radioactive source
    - Possible restrictions of pregnant workers

The Linear Accelerator

Electron acceleration, microwave production, accelerator components,

The Linear Accelerator



The Linear Accelerator

- Components (Figure 1-7 of of Hendee)
  - DC Power Section
  - Microwave Power Section
  - Accelerator Guide
  - Treatment Head

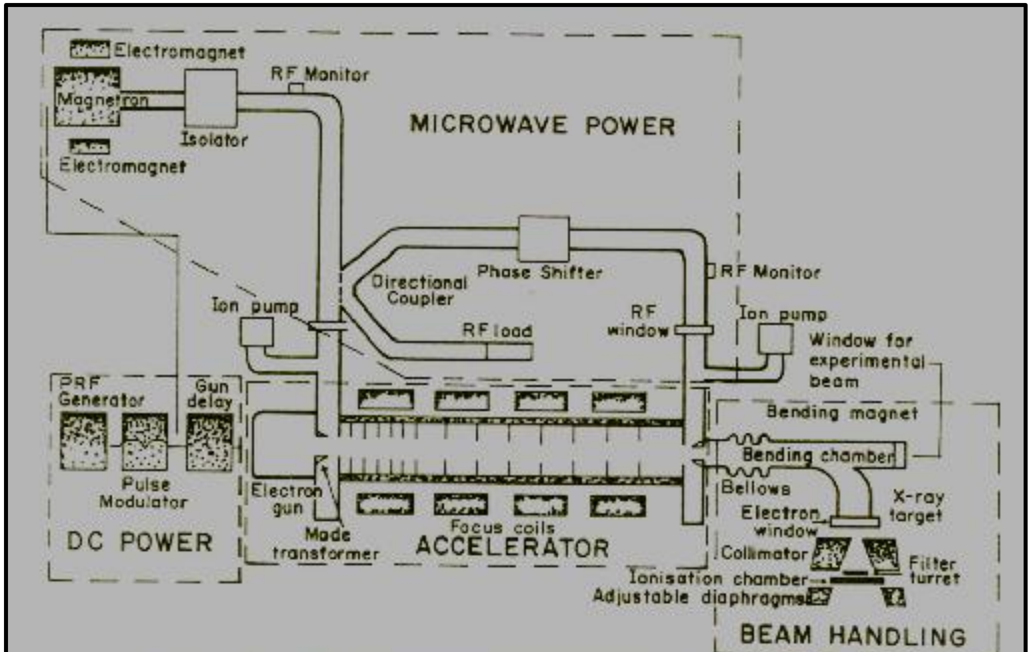


Fig 1–7.—The four major compartments of a linear accelerator.

The Linear Accelerator

- DC Power Section
  - Produces properly-shaped pulses of DC power; these pulses are shaped in the *pulse-forming network* of the *modulator* and delivered to the *electron gun* and microwave power section at the proper frequency through a high-voltage switching device (the *thyratron*).

The Linear Accelerator

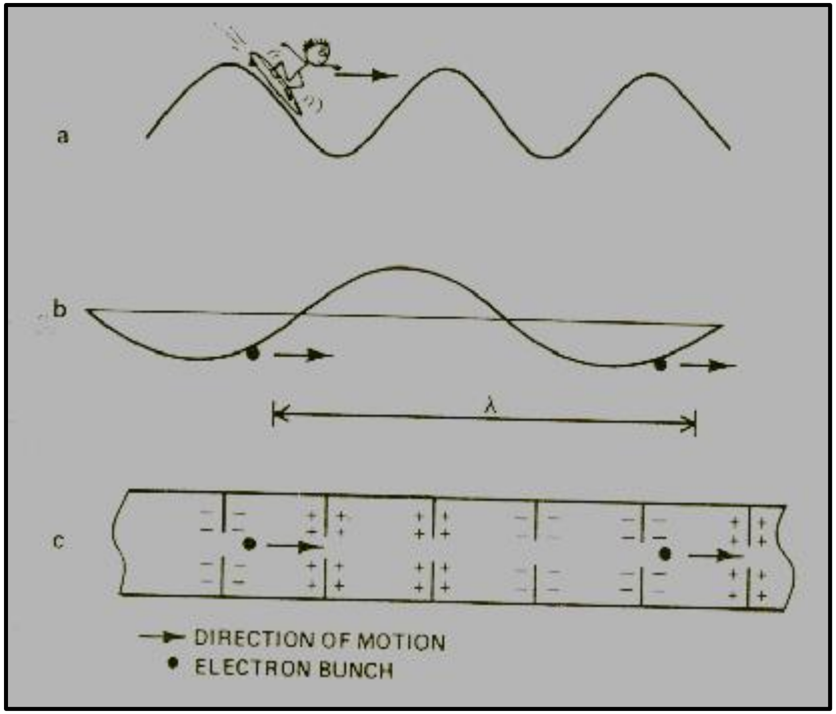
- Microwave Power Section – Provides microwave power amplification (utilizing either a *magnetron* or *klystron*) and transmits the amplified microwaves to the *accelerator guide*.
- Accelerator Guide – A cylindrical tube in which electrons, injected by the electron gun, are accelerated by the amplified microwaves. The accelerated electrons exit the waveguide and enter the *treatment head*.

The Linear Accelerator

- Treatment Head
  - Contains the beam shaping, steering, and control components of the linear accelerator. These components are: the *bending magnet*, *x-ray target*, electron *scattering foils* (most accelerators), x-ray *flattening filter*, *dose monitoring chambers*, and *beam collimation* system.

Microwave Power

- Electrons gain energy through continued exposure to an increasing electric field
- The process is analogous to a "surfer riding a wave" (Figure 28 of Karzmark)
  - Microwave cavities create that environment – they are machined to dimensions that *resonate* at microwave frequencies (S-Band accelerators – 3000 MHz)



Microwave Power

- In a fashion similar to that by which electrons gain energy from microwaves, microwave power can be amplified by the deposition of electron kinetic energy if electrons (grouped in "*buncher*" cavities) arrive in "*catcher*" cavities at the cavities' resonant frequencies (Figure 4.7 of Khan)

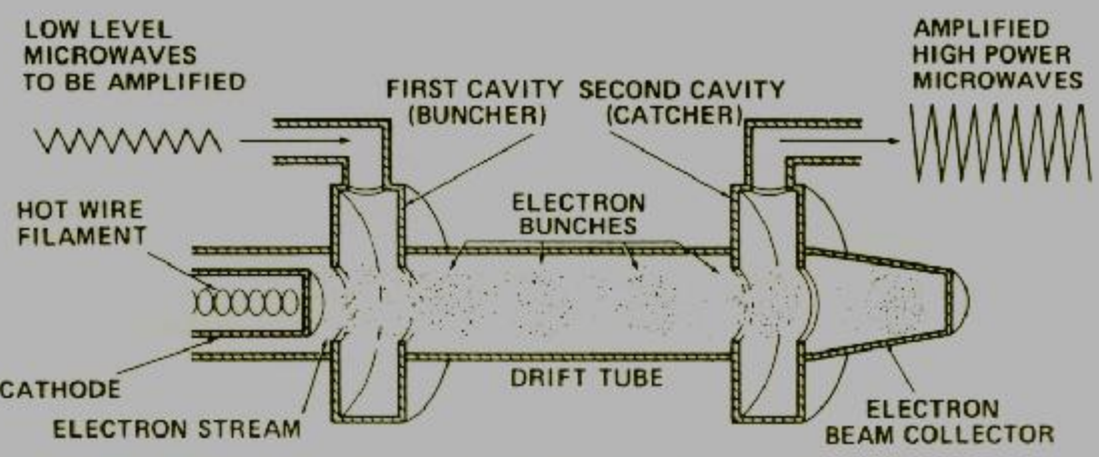
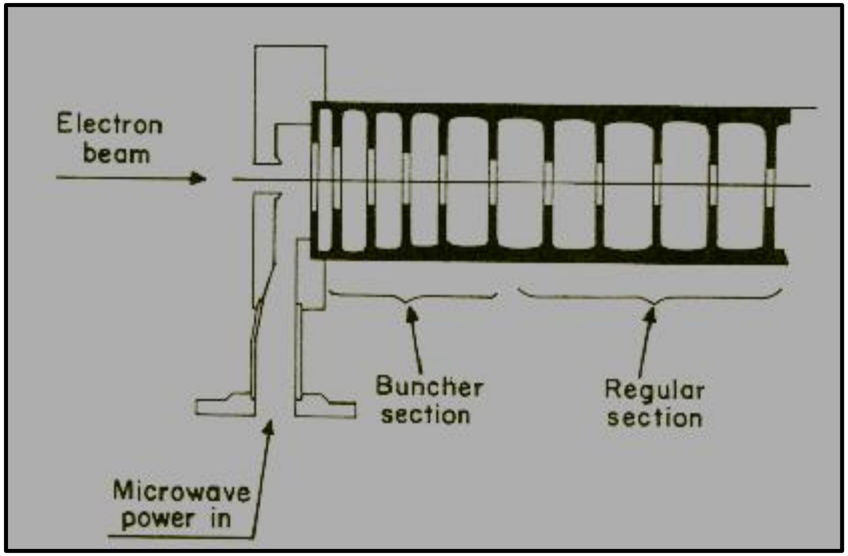


Figure 4.7. Cross-sectional drawing of a two-cavity klystron. From Karzmark CJ, Morton RJ. A primer on theory and operation of linear accelerators in radiation therapy. Rockville, MD: U.S. Department of Health and Human Services, Bureau of Radiological Health, 1981.

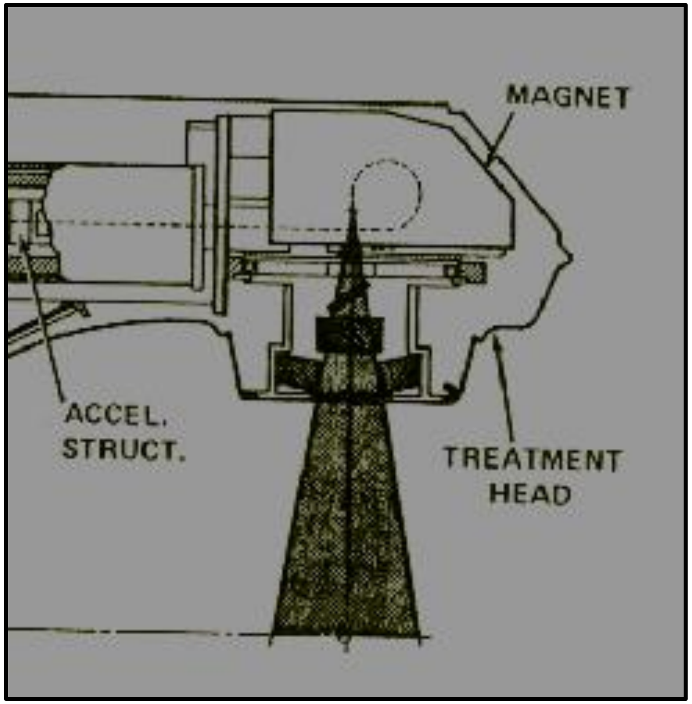
Electron Acceleration

- Electrons can be accelerated in microwave cavities that are arranged in a linear configuration such that the microwaves' "*phase velocity*" is matched to the velocity of the electrons traveling through the guide (Figure 1-11 of Hendee).
  - (Note that energy gain will be proportional to waveguide length.)



The Treatment Head

- Shielded Housing – lead shielding reduces unwanted radiation
- Bending Magnet – provides electron energy selection
  - the magnetic field intensity B is set such that electrons possessing the appropriate energy (momentum $m_e v$) are bent through the radius r that allows passage through the magnet's exit port:
    - $m_e v \propto B\,r$



The Treatment Head

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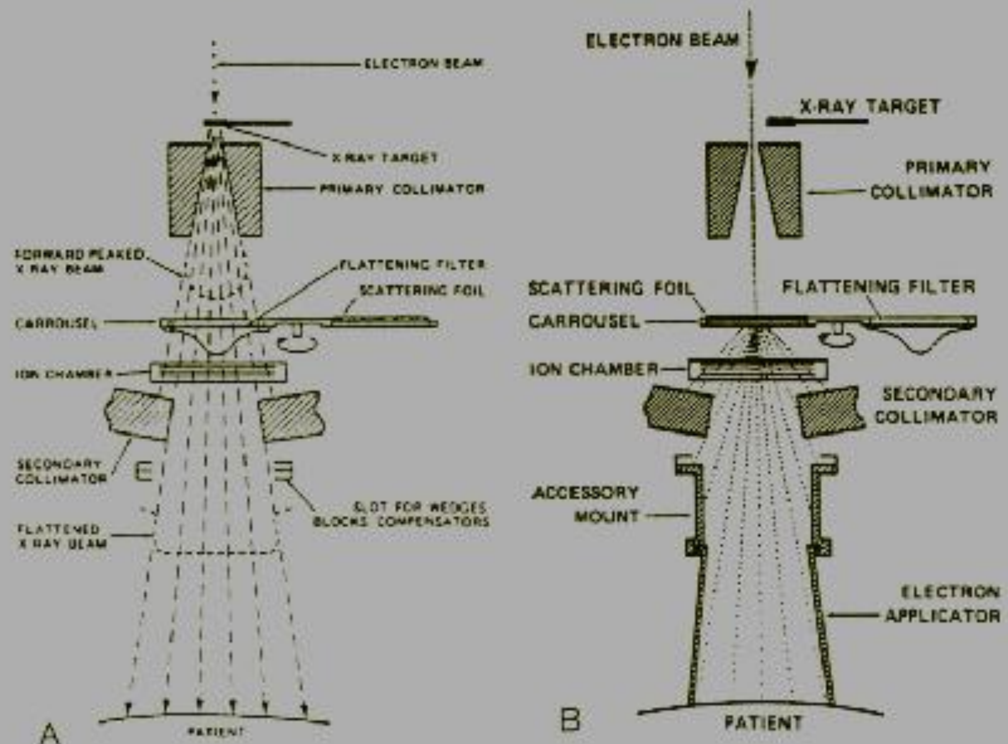

Figure 4.8. Components of treatment head. **A**, X-ray therapy mode. **B**, Electron therapy mode. From Karzmark CJ, Morton RJ. A primer on theory and operation of linear accelerators in radiation therapy. Rockville, MD: U.S. Department of Health and Human Services, Bureau of Radiological Health, 1981.

The Treatment Head

- X-Ray Target – transmission-type tungsten target in which electron produce bremsstrahlung radiation; inserted only during x-ray beam production, removed during electron-beam production
- Flattening Filter – (photon beams) metal filter placed in the x-ray beam to compensate for the "forward peaked" photon distribution and produce a "flat" beam

The Treatment Head

- Scattering Foils – (electron beams) thin metallic foils inserted in the electron beam to spread the beam and obtain a uniform electron fluence
- Monitoring Chambers – transmission ionization chambers used to monitor dose rate, total integrated dose and beam symmetry.
- Collimation System – fixed and movable beam limiting devices, normally made of lead, used to shape and size the beam

Other Megavoltage Units

- The Van de Graaff Generator
  - is an electrostatic accelerator; the unit accelerates electrons to approximately 2 MV.
  - electrons are "sprayed" onto a moving belt where they are transported to a metallic dome and allowed to accumulate.
  - The accumulation of charge creates a high potential difference relative to ground. This potential is applied across an x-ray tube.
  - (Figure 4.4 of Khan)

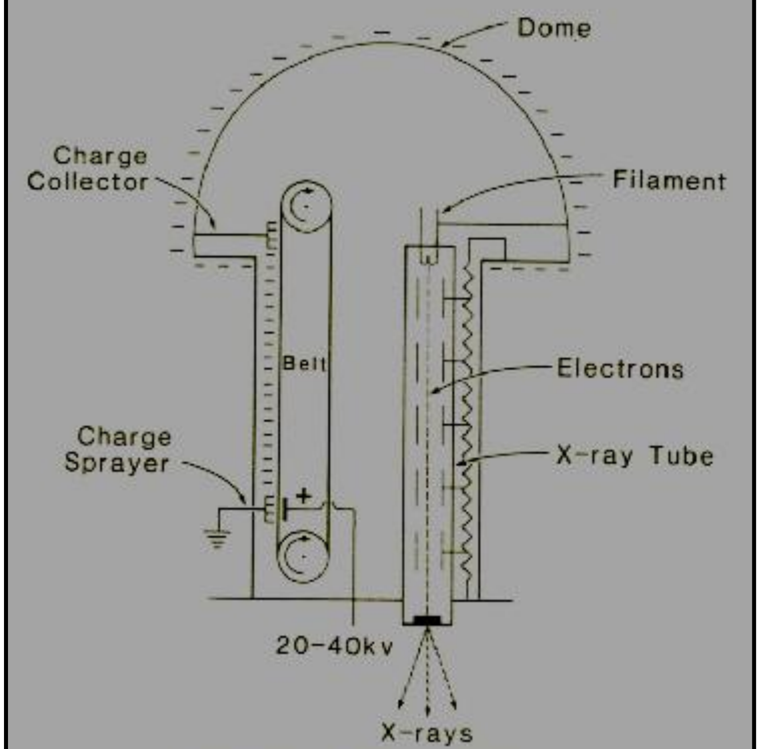

Figure 4.4. A Van de Graaff generator.

Other Megavoltage Units

- The Betatron
  - Electrons contained in an evacuated hollow "donut" are accelerated by an alternating magnetic field of increasing intensity
  - Electrons are "removed" from their orbit after attaining the proper energy by introducing a sudden reduction in the magnetic field; electrons are then allowed to strike either an x-ray target or scattering foils

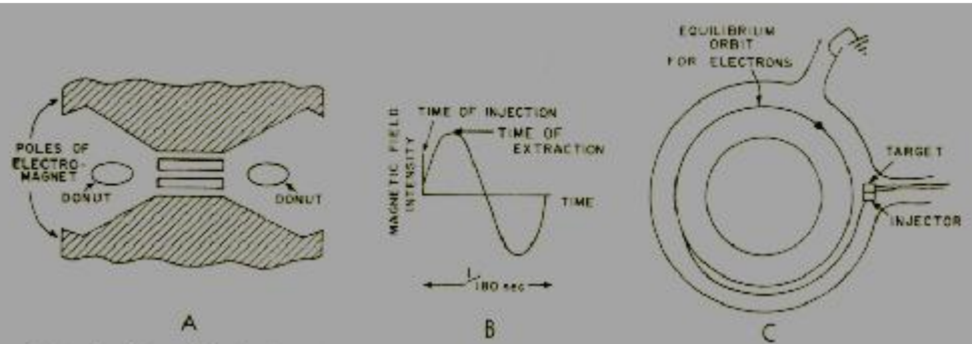

Fig 1–16.—Principles of a betatron: *A*, cross section illustrating the electromagnet and the donut; *B*, graph of the intensity of the magnetic field across the electron orbit as a function of time. Times for injection and extraction of electrons are denoted. The power supply oscillates at a frequency of 180 Hz. *C*, path of electrons in a betatron donut. The electron injector and x-ray target are indicated. (From Hendee W.R.: *Medical Radiation Physics*, ed. 1. Chicago, Year Book Medical Publishers, 1970.)

Other Megavoltage Units

- The Cyclotron
  - Two hollow semi-circular electrodes (called "Dees") are mounted between the poles of an electromagnet; an alternating potential is applied to the dees which are separated by a small gap
  - Positive ions (e.g. protons) are released into the center of the dees and are attracted to the negative dee where they enter into a circular orbit.
  - The alternating potential is timed so that the electric fields change direction as the particles emerge from the first dee. The particles are then accelerated to the second dee where the process is repeated.
  - Each time the positive ions traverse a gap they gain energy. As they gain energy, the radius of their circular orbit increases until they are removed.

The Cyclotron

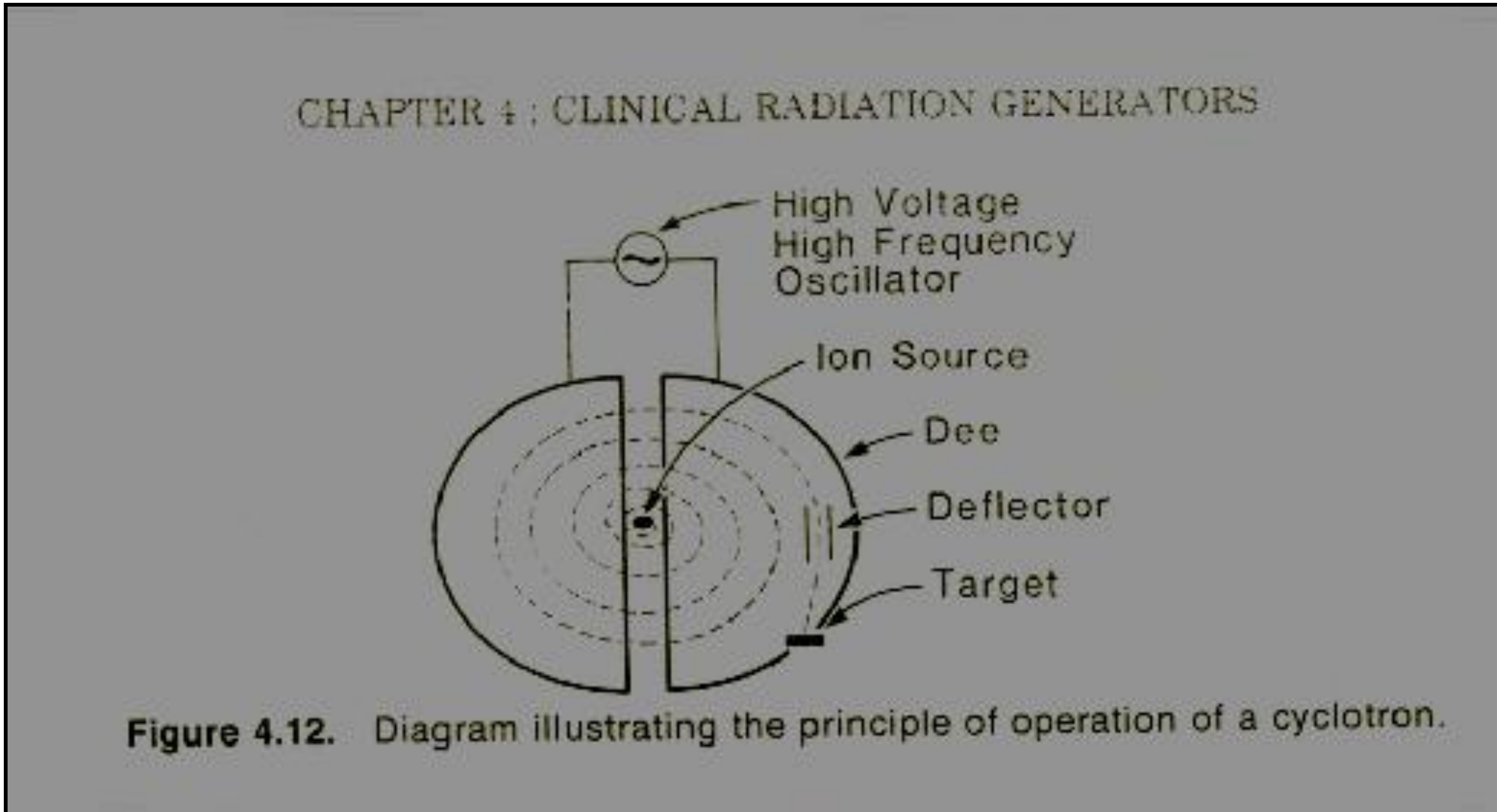
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Figure 4.12. Diagram illustrating the principle of operation of a cyclotron.

From: Khan

Heavy Particle Beams

- Heavy *charged* particles, such as protons, are produced, more commonly for therapy, in cyclotrons.
- Due to their charge and increased mass, heavy charged particles deposit most of their energy at the end of their range, producing what is known as a Bragg peak.
- Figure 4.16 of Khan

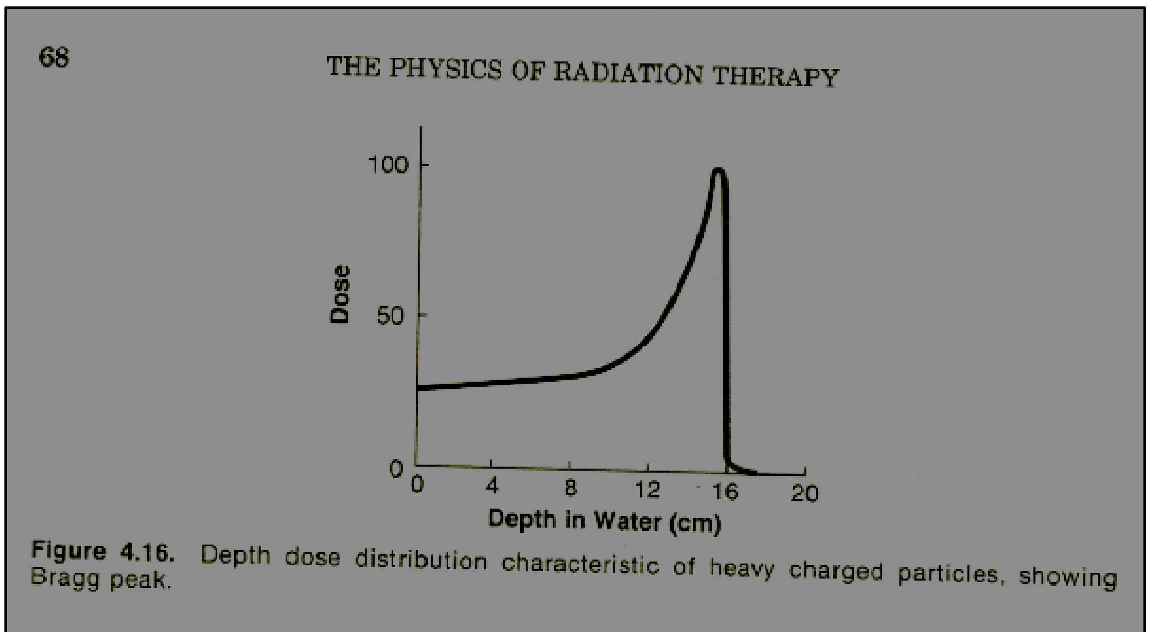

Figure 4.16. Depth dose distribution characteristic of heavy charged particles, showing Bragg peak.

Summary

- External Beam Therapy Units
  - Most Important Components
- Radionuclide Teletherapy Units: Co-60 Teletherapy
- X-Ray Units
  - X-ray production
  - The Linear Accelerator
- Other External Beam Units

Thank You