Chapter 4
High Energy Machines

Radiation Dosimetry I


Outline
• Brief history of radiation generators
• Betatrons
• Cyclotrons
• Linear accelerator: resonant cavities, magnetrons, klystrons, and waveguides
• Linear accelerator: components of the accelerator head
  – Theromotherapy

General considerations for high-energy machine
• Depth-dose properties:
  – High penetration
  – Delivery of maximum dose at a depth
  – Minimal low-energy electron contamination
  – Skin sparing
• Field flatness (not a requirement anymore)
• Constant output and monitoring
• Sharp field edges (penumbra)

Evolution of radiation generators
1895 - Roentgen discovers X-rays
1913 W.E. Coolidge develops vacuum X-ray tube
1931 E.O. Lawrence develops a cyclotron
1932 1MV Van de Graaff accelerator installed, Boston, MA (USA)
1939 First medical cyclotron for neutron therapy, Crocker, CA (USA)
1946 20MeV electron beam therapy with a Betatron, Urbana, Ill. (USA)
1952 First Co-60 teletherapy units, Saskatchewan (Canada)
1956 First 6MeV linear accelerator, Stanford, CA (USA)
1958 First proton beam therapy (Sweden)
1959 First scanning electron beam therapy, Chicago, Ill. (USA)
1976 First pion beam therapy, LAMPF, NM (USA)
1990 First hospital based proton therapy, Loma Linda, CA (USA)
1994 First C-ion facility HIMAC (Heavy-ions Med. Accelerator in Chiba, Japan)


Betatrons
• Device for accelerating electrons
• Electrons from a filament are injected
• AC magnet performs two functions:
  – Electrons are bent into a circular path
  – Changing magnetic flux creates E-field accelerating electrons

• Electrons spiral inward until reach equilibrium orbit
• They are accelerated as they travel around at equilibrium orbit

Evolution of radiation generators

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Betatrons

- As the electrons get faster they need a larger magnetic field to keep moving at a constant radius orbit, which is provided by the increasing magnetic flux.
- After electron attains its maximum energy (pt. C) the field at the orbit is decreased, and electron spirals outward to strike the target.
- Betatron can be a source of electrons or x-rays (with a target).
- Radiation is produced in pulses.
- Efficiency is very high, but the dose rate could be low due to inefficient injection of electrons.

Example 1

- A long solenoid has a diameter of 2B=12 cm. When a current I exists in its windings, a uniform magnetic field of magnitude B=30 mT is produced in its interior. By decreasing I, the field is caused to decrease at the rate of 6.5 mT/s. Calculate the magnitude of the induced electric field E at r=8.2 cm from the axis of the solenoid.

\[ E = \frac{\mu_0 I}{2\pi r} \] 

A. 10.0 mV/m 
B. 31 mV/m 
C. 75 mV/m 
D. 143 mV/m 
E. 200 mV/m

Example 2

- A deuteron (m=3.34x10^{-27} kg) circulates in a cyclotron of radius 53 cm and operating frequency 12 MHz, beginning approximately at rest at the center. The electric potential between D’s is 80 kV. How many passes will it complete before reaching the edge of the cyclotron?

\[ v = \frac{2nBq}{m} \] 

A. 80 
B. 105 
C. 130 
D. 150 
E. 200

Cyclotron

- For sources of protons and other heavy particles.
- Massive particle moves through relatively small potential difference many times.
- Magnetic field is used to bring the particle to an accelerating region.
- High-frequency oscillator creates potential difference between D’s and is used for acceleration.

Linear Accelerators

- A charged particle can be accelerated while moving through a potential difference between two electrodes.
- Arranging electrodes in a certain configuration and using electromagnetic wave rather than a static potential difference allows for higher beam energies and intensities.
- Two main components: power source and resonant cavity.

Example 1

\[ F = Bqv \quad \frac{mv^2}{r^2} = Bqv \]

\[ t_s = \frac{2m}{v} \quad \frac{2m}{Bq} \]
Linear Accelerators

- **I. POWER SOURCE**
  1. Why not DC: Problems of electrical breakdown, physical size of electrical equipment
  2. Apply technique of repeated pulses, $V = nv$
     - Need oscillating form of power supply
  3. Leads to principle of cyclic and linear accelerators
  4. Wavelength has to be short enough to accelerate electrons in a reasonable distance
  5. S-band microwave technology, developed for radar in WWII, has a frequency of ~ 3 GHz or $\lambda = 10$ cm
  6. High power is also needed to ensure sufficient energy gain per cycle.

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- **II. RESONANT CAVITY FOR GENERATION OF HIGH POWER MICROWAVE PULSES:**
  1. At high frequencies, ordinary resonant circuits become impractical. Also, problems of radiation loss
  2. Hollow cavities as resonant circuits (skin effect)
  3. The quality factor, or Q value, of a resonant circuit or cavity is defined as $Q = \frac{\text{energy stored in cycle}}{\text{energy lost in cycle}}$
     - For a circuit, $Q \sim 10^2$
     - Whereas for a cavity, $Q \sim 10^4$
  4. Achieved through devices called magnetrons and klystrons
  5. Cavity resonators feature in both power sources and accelerating structures

ROLE OF RESONANT CAVITIES IN LINEAR ACCELERATORS
  1. Cavity acts as an acceleration module
  2. Multiple cavity arrangement can act as an RF amplifier - klystron
  3. Multiple cavity arrangement can act as a high power oscillator - magnetron

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**Cavity Principle**

- Microwave cavity design is derived from a simple resonant circuit. The components of such a circuit need to become smaller as the resonant frequency increases
- The capacitor, resistance and inductance become the faces and sides of a pill box such that the entire surface is made of conducting material
- When this cavity is excited, strong electric fields are generated perpendicular to the faces that alternate in sign with the frequency of the oscillation

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**Example 3**

21. A one microfarad capacitor is connected in series with a $1 \times 10^6$ ohm resistor. At time $t = 0$, a 100 volt power supply is connected to the circuit. At 100 seconds, what is the voltage across the capacitor? (See Figure below.)

- $V_0 + U - IR = 0$; $I = \frac{\text{dq}}{\text{dt}} = \frac{d(CU)}{\text{dt}}$
- $V_0 + U - RC \frac{dU}{dt} = 0$
- $\frac{dU}{dt} = \frac{V_0 - U}{RC}$
- $U = V_0[1 - e^{-t/RC}]$

RC = $100 \times 10^6 \times 10^{-5} = 100$

$U = V_0[1 - e^{-t/RC}] = 100[1 - e^{-100}] = 100 \times 0.632 = 63.2$

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**Cavity Principle**

- In general, $\omega \sqrt{LC} \sim Q$ for a resonant circuit, so one needs very small L and C to obtain high frequencies; use of cavities as a form of resonant circuit since they have low L and C
- Only the electric field plays a role in electron acceleration (along the axis of a cylindrical cavity)
- Electric field configuration in cylindrical microwave cavity with hole on axis for electrons to pass through is only slightly modified
- Efficient transfer of energy to electron beam, e.g., low energy losses, since $Q \sim 10^4$ for a resonant circuit $Q = 50^4$ (where $Q = \frac{f_0}{2\Delta f}$ and $2\Delta f$ is FWHM), whereas for a cavity, $Q \sim 10^6$

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Example 4

- Determine the lowest frequency allowed in a cubic microwave oven of linear dimension of \( a = 30 \text{ cm} \).

\[
\begin{align*}
\text{A.} & \ 0.1 \text{ GHz} \\
\text{B.} & \ 0.2 \text{ GHz} \\
\text{C.} & \ 0.5 \text{ GHz} \\
\text{D.} & \ 1 \text{ GHz} \\
\text{E.} & \ 5 \text{ GHz}
\end{align*}
\]

\[
\lambda = \frac{2\pi}{n}\lambda \\
\lambda = 2 \times 30 = 60 \text{ cm}
\]

\[
v = \frac{c}{\lambda} = 3 \times 10^8 / 60 = 5 \times 10^7 = 0.5 \text{ GHz}
\]

Magnetron

- Generator of microwaves
- A cylindrical anode (A) has the cathode (K) along its axis.
- Magnetic field is directed along the axis of the cylinder
- Magnetic field bends the electron trajectory, and accelerating electron emits energy in microwave range
- The magnetic field has to be high enough to provide electron collection, but low enough to avoid electron accumulation at K

Current between anode and cathode is not used in a power source

If it stops the magnetron is blocked due to electron accumulation around the cathode

The circulating electrons induce a charge distribution between adjacent segments of the anode
This, in turn, perturbs the electron orbits shaping the space charge distribution into a form resembling the spokes of a wheel
The resonant cavities gain energy from the orbiting electrons which are slowed and eventually spiral into the anode, leading to anode current

Klystron

- Klystron is a microwave amplifier
- Low-power signal is supplied to the “buncher” cavity, its E-field modulates velocities of electrons, which then merge into bunches going through the drift tube
- Amplified signal is collected from “catcher” cavity, where electrons decelerate emitting at the same resonant frequency
Klystron

- The electron gun 1 produces electrons
- The bunching cavities 2 regulate the speed of the electrons (ac field accelerates slow electrons and slows down fast ones) so that they arrive in bunches at the output cavity
- The bunches of electrons decelerate and excite microwaves in the output cavity 3 (E-filed of the same frequency but polarity opposite to that applied in bunching cavities)
- The amplified microwaves flow into waveguide 4, to the accelerating structure
- The electrons are absorbed in the beam stop 5
- Usually klystrons have multiple amplifying cavities

http://www2.slac.stanford.edu/vvc/accelerators/klystron.html

Waveguides

- The velocity of the wave is matched with the velocity of the electron at time of injection
- Disk spacing is gradually increased to correspond to velocity v down the waveguide

The length of the accelerating waveguide depends on the final electron E: ~30 cm at 4 MeV; ~150 cm at 25 MeV

Accelerating waveguides

- Most linacs use waveguides operating at 3000 MHz (S-band microwaves)
- Compact waveguides (used in CyberKnife, Tomotherapy) operate at 9000 MHz (X-band)

Example 5

- What is the minimum size of a cubical cavity in a standing wave waveguide for 3000 MHz microwaves?
  A. 2 cm
  B. 3 cm
  C. 5 cm
  D. 10 cm
**Medical linacs**

- Most use isocentric mounts with the distance of 100 (80) cm to the axis of rotation
- The center of the tumor is positioned at the axis

**Medical linacs**

- Various components serve a purpose of delivering flat (or not) beam with pre-defined field sizes and adequate shielding beyond the target
- Ion chamber is used to monitor the output

**Tomotherapy**

- A linac is mounted on a CT-like ring gantry
  - Conformal treatment (MLC)
  - Image guidance (MV imaging)
- The source can move either through a set of discrete angular positions or helically
- First patient treated in 2002

**Summary**

- Particle accelerators: circular and linear
- High energy x-ray machines use electron accelerator and a target
- Using electromagnetic wave rather than a static potential difference allows for higher beam energies and intensities

**Additional reading**

- Podgorsak, E.B., Radiation Oncology Physics Handbook, IAEA 2005, Chapter 5 (available online)