Radiation Generators

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Radiation Generators

Topics to be Covered:

A. Kilovoltage x-ray units
B. Cobalt teletherapy units & Gamma Knife
C. Linear accelerators, Tomotherapy, Cyberknife & IORT
D. Cyclotron (protons)
E. Properties of megavoltage beams
Evolution of Radiation Generators

1895
- X-Rays

~1951
- Cobalt-60
- Betatrons

~1962
- Linear accelerators
- Van de Graaff generators

Present
- Cyclotrons
- Gamma knife
- Synchrotrons
- Viewray
- Cyberknife
- Tomotherapy
- Radium therapy

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Kilovoltage Therapy Units (Non-Isocentric)

- **Contact therapy (≤ 50 kV):**
  - Often short SSD, high dose rate machines with small applicator sizes
  - HVL < 2mm Al, with sharp dose fall-off for skin irradiation

- **Superficial therapy: (50-150kV):**
  - SSD’s typically up to 20 cm
  - HVL up to 8mm Al (150kV)

- **Orthovoltage therapy (150-500kV):**
  - Typical energies are 250 and 300 kV with SSD’s up to 50cm
  - HVL up to 4mm Cu

All beam qualities have maximum dose at or close to the surface and use fixed applicator treatment. 250 kVp is the “gold standard” for radiobiology.
Orthovoltage Unit – Mainstay of Early Radiation Therapy

1. Stationary, scatter target (W in Cu block)
2. HVL ~ mm Cu
3. Dose rate (current machines):
   - ~260 R/min; HVL = 1 mm Cu
   - ~180 R/min; HVL = 2 mm Cu
   - 50 cm SSD
4. Target angle is ~26°-32° for large field size (20x20)
5. Tube is oil cooled
Orthovoltage Applicators – SSD $R_x$

BJR specifies PDDs for both diaphragm limited fields and closed applicators.
Cobalt-60 Teletherapy Units

• Source drawer contained in thick, steel encased lead housing to reduce leakage to <0.02 mSv/hr at 1m
• Safety systems ensure that the unit fails in the “OFF” position
• Depth of maximum dose is 0.5 cm for a 10x10 cm\(^2\) field; this drops rapidly with increasing field size due to electron contamination
• \(^{60}\text{Co}\) is still the standard beam quality for calibrating ionization chambers (\(N_{D,W}\) & \(N_x\))
• These units now come under homeland security regulations
Theratron 780 - Cutaway View

Cutaway drawing of Theratron 780 Sourcehead.
Cobalt 60 Source Construction

1. Source comes with a min. diameter of 1.5cm and can either be in the form of pellets or a solid slug. Thus, the penumbra is much worse than for linacs.

2. Clinical sources are typically $10^4$ Ci, giving ~240 rad/min at isocentre (80 cm).

3. Doubly encapsulated source
Cutaway of Gamma Knife

Activity on loading = 6600 Ci

Slide courtesy of Elekta
Overview of Linac Components

- Gun
- Waveguide
- Power supply
- Modulator
- Treatment Head
WHAT KIND OF POWER SOURCE IS NEEDED FOR LINEAR ACCELERATORS?

1. Why not DC?
   - Problems of electrical breakdown; physical size of electrical equipment

2. Apply technique of repeated pulses, viz.
   \[ V \approx n v \]
   - 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 $\sim 3 \text{ GHz}$, or $\lambda \approx 10 \text{ cm}$

6. High power is also needed to ensure sufficient energy gain per cycle.
GENERATION OF HIGH POWER MICROWAVE PULSES

1. At high frequencies, ordinary circuits become impractical (radiation loss, skin effect)

2. Hollow cavities as a form of resonant circuit

3. The quality factor, or Q value, of a resonant circuit or cavity is defined as

\[ Q = \frac{\text{Energy stored in cycle}}{\text{Energy lost per cycle}} \]

For a circuit, \( Q = 10^2 \), whereas for cavity, \( Q = 10^4 \)
Cavity Principle

\[ \omega \sim (LC)^{-1/2} \]
GENERATION OF HIGH POWER MICROWAVE PULSES

1. Achieved through devices called magnetrons and klystrons

2. To understand these devices, need to consider properties of cavity resonators

3. Cavity resonators feature in both power sources and accelerating structures
Cavity Principle - I

Current Charge  E-field  H-field
Cavity Principle - II

Current Charge  E-Field  B-Field
Cavity Principle - III

Current Charge  E-field  B-field
ROLE OF RESONANT CAVITIES IN LINEAR ACCELERATORS

1. Cavity acts as an acceleration module

2. Multiple cavity arrangement can act as RF amplifier
   - klystron

3. Multiple cavity arrangement can act as a high power oscillator
   - magnetron
Magnetron Principle

Illustrating the theory of the cylindrical magnetron

$B_c$ depends on electron velocity and hence accelerating voltage
Magnetron Principle - II

Increasing the magnetic field eventually leads to a sudden drop in current

Theoretical Cut-off value: 100 Gauss
Magnetron - Detail

Approximately 2MW peak power for 4 MV
Magnetron Action - I

Charge +,- From $E_p$
Charge +,- From $E_m$

Anode
Drift Space
Cavity

$E_m$
$E_p$

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Magnetron Action - III

Space-Charge distribution and electron paths in an 8-cavity magnetron, when oscillating.
Principle of Klystron

Low level microwaves to be amplified

First Cavity (Buncher)

Second Cavity (Catcher)

Amplified high power microwaves

Hot wire filament

Cathode

Electron Stream

Drift Tube

Electron Bunches

Electron Beam Collector

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Klystron with Four Sections

approx 20 MW peak power
Acceleration Principle of Waveguide

surfing analogy!
Principle of Phase Stability

Electric field forces particles to “bunch”

Principle discovered independently by Veksler (1944) and McMillan (1945)
Disc-Loaded Waveguide

$v_{ph} > c$

$v_{ph} < c$
Travelling Waveguide

The amplitude of the e/m wave progressively decreases along the guide.

Remaining beam power is dumped at the end.
Mass-Energy Relation for Electron

As energy increases, so does velocity

$v_e = f(V)$  $v_e \approx c$  $V = \text{Energy MeV}$

$c = \text{velocity of light}$

Electron Velocity $v_e$

Electron Mass $m$

$m = m_0$
Cut-Away of Travelling Guide

gun end

narrower

closer

wider
Standing WG principle - I
Standing WG principle - II

E Field Maxima
Standing WG principle - III

Note: the overall e/m amplitude decreases with beam loading

E Field Maxima
Standing WG - Schematic

note that travelling waveguides are longer than standing waveguides due to side coupled cavities.
Waveguide for 4 MV Linac
Schematic of Waveguide
Electron Beam Current, X-Ray output vs. Electron Energy
X-Ray Output for Various Energies

Beam Loading:
- a. heavy
- b. optimal
- c. light
Schematic of Energy Switch

- Fully closed – field reversal
- Partially closed – field reduction
Principle of Energy Switch

Purdy & Goer, NIMRIP:B 11:1090-1095; 1985

Also used in the Mobetron IOERT machine

Fig. 2. Dual accelerator structure illustrating the switched-guide concept used on the Varian Clinac 1800.
X-Ray Outputs with Energy Switch

- **6x Mode**
  - 6% Slit

- **18x Mode**
  - 6% Slit

<table>
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<tr>
<th>Energy (MeV)</th>
<th>Relative Beam Intensity</th>
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<tr>
<td>0</td>
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<tr>
<td>20</td>
<td>2.0</td>
</tr>
<tr>
<td>22</td>
<td>2.2</td>
</tr>
</tbody>
</table>
In-Line, No Magnet Linac
WG Parallel to Rotation Axis

- Gantry
- Accelerator Structure
- Beam
- Bending Magnet
- Axis of Gantry Rotation

Scale: Feet 0 2 4 6 8 10
WG at Angle Relative to Rotation Axis

Note that Elekta machines use a travelling w/g without a pit for the gantry and a magnetron instead of a klystron.
90° vs. 270° Magnet Schemes

Alternative Magnet Schemes

Gantry Mounted Accelerator

Quadrupole Focusing

Magnet Pole

Energy Defining Slits

Target

Accelerator

Rotating Magnet System

Quadrupole Focusing Magnets

Slits

Non-uniform Field Magnet

Rotating Vacuum Joint

Achromatic Three Magnet System

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Beam Envelope of X-Ray Production
note that the flattening filter design is a compromise between flat fields at small and large field sizes – hence the horns at max. field size
Flattening Filter, Scattering Foil Carousel

- Flattening filter
- Scattering foil
- Clinac 18
Top of Gantry (at 270°)

Energy switch
High Energy Linac With No Covers
Thin vs. Thick Target Spectrum

"Thick" implies almost equal to the electron range, e.g. about 1/10" for $E_{\text{max}} = 10 \text{ MeV}$

Medical Linac Tungsten
Thick*Target "Soft" Spectrum

Medical Betatron
Thin Target "Hard" Spectrum

Relative Intensity vs. Beam Energy $E/E_{\text{max}}$
Expected Fluence Spectra for Various Target, Flattening Filter Combinations

Rawlinson JA & Johns HE
Am. J. Roentg. 118:919-922;1973
Total Attenuation Coefficient for Carbon, Aluminum, Copper and Lead

Photon energy

Mass coefficient (m^2/kg)
10 MeV Primary Spectrum (0° to 15°)

annihilation peak

Monte Carlo calculation
# Average Photon Energy (MeV) of Primary Radiation for Various Incident Electron Energies

<table>
<thead>
<tr>
<th>Angle (degrees)</th>
<th>Electron Kinetic Energy</th>
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<tbody>
<tr>
<td></td>
<td>6 MeV</td>
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<tr>
<td>0-15</td>
<td>1.76</td>
</tr>
</tbody>
</table>
Clinical X-Ray Beam Production
Scattering Principle for Electron Beams

- X-Ray Target
- Electron Beam
- Scattering Foil
- Movable Target and Foil Holder
- Scattered Electrons
- Primary X-Ray Collimator
- Electron Collimator

* Copper or Lead
  About 0.02" Thick
Clinical Electron Beam Production

Current e-applicators have a space (~5 cm) between the bottom of the applicator and 100 cm SSD for patient setup.
Overall Layout of Linac Head (Varian)

- Retractable X-ray target
- Bending magnet assembly
- Electron Orbit
- Flattening Filter
- Scattering Foils
- Dual Ionization Chamber
- Field defining light
- Range finder
- Collimators
- Isocenter
Cyberknife

(slides courtesy of Xing-Qi Lu, BID Medical Center)
Linear Accelerator

- 330 lbs. (150 kg)
- 6 MV X-band
  - 9.3 GHz microwaves
- 400/600 MU/min
- 12 circular collimators
  - 5 to 60 mm
Imaging System

- 2 diagnostic X-Ray sources
- 2 image detectors (cameras)
- Patient imaged at 45° orthogonal angles
- Live images
The Mobetron IORT Machine is also an X-Band Machine
Tomotherapy: Under the Covers

- Gun Board
- Linac
- Control Computer
- Circulator
- Magnetron
- Pulse Forming Network and Modulator
- Data Acquisition System
- Beam Stop
- Detector
- High Voltage Power Supply

Note: VERO system is similar to this but can adjust MLC for target motion.

Slide Courtesy of Tomotherapy, Inc.

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The \((\gamma,xn)\) and \((\gamma,ln)\) cross sections for \(^{208}\text{Pb}\). The \((\gamma,xn)\) and \((\gamma,ln)\) cross sections are represented by crosses and plus signs, respectively. Above 14.9 MeV the \((\gamma,ln)\) cross section includes an unknown component from the \((\gamma,pn)\) reactions (Veyssiere et al, 1970).
Neutron yield vs energy, Z

Neutron yields from semi-infinite targets of various materials per unit incident electron-beam power as a function of incident electron energy $E_0$ (Swanson, 1979).
Photoneutron Energy Spectra

Photoneutron spectra for tantalum with peak bremsstrahlung energies of 20 and 30 MeV. A fission neutron spectrum is shown for comparison (NCRP, 1964).
Neutron Leakage: In-Beam

Neutron Rad Dose * %

Photon Rad Dose

Accelerator Energy (MeV)
Neutron Leakage: Out-of-Beam

Neutron Rad Dose \times \%  
Photon Rad Dose

Accelerator Energy (MeV)

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What to check after changing a ……

<table>
<thead>
<tr>
<th>Machine</th>
<th>Component</th>
<th>Energy</th>
<th>PDD</th>
<th>Profiles</th>
<th>Dose calibration</th>
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<tr>
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<td>Magnetron</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td></td>
<td>Ion chamber</td>
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<td>X</td>
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<tr>
<td></td>
<td>Tgt/gun/guide</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>With magnet</td>
<td>Klystron/magnetron</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Gun</td>
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<tr>
<td></td>
<td>Ion chamber</td>
<td></td>
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<td>X</td>
<td>X</td>
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<tr>
<td></td>
<td>Foil/flattening filter</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
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<tr>
<td></td>
<td>Guide</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Bending magnet</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Cyclotron

- particles travel in circular orbit, constrained by magnetic field.
- particles are accelerated by RF field applied between two D's between which the particles pass.

- Revolution time, $t = pM / (H \times e)$, independent of velocity or radius.
- Max energy limited by mass increase of particle (22 MeV for d). Higher energies can be achieved by modulating the frequency of the RF system. Such a machine is called a synchro-cyclotron.
Variation of Percent Depth Dose with Energy

Change in $d_{\text{max}}$ With energy
Variation of Percent Depth Dose at Field Size for 4 MV Photons

Depth in Water (cm)

Percent Depth Dose

Little change in $d_{\text{max}}$

Increase due to scatter radiation

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Much less side scatter at high energies

Significant change in $d_{\text{max}}$ with field size
As one would expect, \( d_{\text{max}} \) increases with energy (range of secondary electrons), but is not linear.

\[
\begin{align*}
\text{Depth of Maximum Dose (cm)} & \quad \text{Beam Energy (MV)} \\
4 \, \text{MV} & \quad 4 \, \text{cm} \\
6 \, \text{MV} & \quad 6 \, \text{cm} \\
10 \, \text{MV} & \quad 10 \, \text{cm} \\
18 \, \text{MV} & \quad 18 \, \text{cm}
\end{align*}
\]
4 MV is constant with field size, but 18 MV is not, due to $e^-$ produced in the head.
Beam Profiles for a 40x40 Field at 18 MV

Relative Dose

Distance (cm)

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Thank you for your attention!
References:

Ford J.C. Advances in accelerator design. AAPM, Medical Physics Monograph #15.
Karzmark C.J. and Morton R.J. A primer on theory and operation of linear accelerators in radiation therapy. Bureau of Radiological Health, FDA 82-8181
More detailed books:


Livingood. Cyclic accelerators
Livingston. High energy accelerators

Segre, G. Nuclei and particles