RADIATION GENERATORS

Physics Review Course
52nd Annual Meeting, AAPM
Philadelphia, PA
July 17th, 2010

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Radiation Generators

A. Kilovoltage units

     1.   Contact units
     2.   Superficial units
     3.   Orthovoltage units

B. Teletherapy units

     1.   Source & housing
     2.   Collimator, penumbra
     3.   Radiation characteristics

C. Linear accelerators

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     2.   Cavity operation
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     12.   Photon/electron beam delivery systems (incl. beam monitoring and collimator
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     13.   Electron linear accelerators with dual-energy photon beams
     14.   Neutron background.
     15.   Other physical characteristics of linear accelerators
   16.   Features of computer controlled linear accelerators

D. Properties of megavoltage beams

     1.   Percent depth dose curves
     2.   Penumbra

A   Kilovoltage units

- Conventional definition is that : (1) *contact* therapy refers to equipment operating with X-rays tubes at an accelerating potential < 50 kV, (2) *superficial* therapy refers to potentials of 50-150 kV and (3) *orthovoltage* unit refers to potentials of 150-500 kV. Other authors have defined these ranges in many different ways, but these ranges generally agree with, or at least overlap, other definitions.

- Maximum dose is at the surface, so clinical use is of these units is often restricted to superficial lesions and, sometimes, intraoperative radiation therapy. Note that currently, there are only two manufacturers of kilovoltage x-ray units. These units offer ranges of beam quality that cover two or three of the classes of therapy (see below).

    1. Contact units:
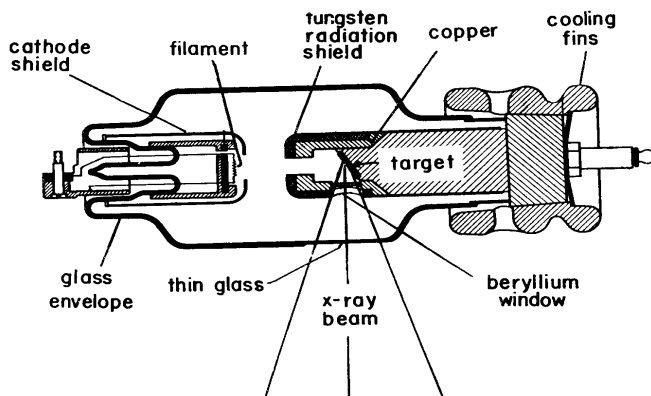
- Beam quality expressed in mm Al
- Short (~ few cm) SSD units

(2,3) Superficial and orthovoltage units:

X-ray units that are currently manufactured cover both the superficial and orthovoltage regions and even the contact regions. For example, Gulmay Medical Ltd. offer a superficial model, 2000, with x-ray energies from 10 to 150 kV and two other models, 3225 and 3300, with x-ray energies between 25 and 220 kV and 40 and 300 kV respectively. Pantak offers two units, the Therapax 150 and Therapax 300, with x-ray energies between 30 and 150 kV and 30 and 300 kV, respectively. Various square, rectangular and circular closed and open ended applicators are available with these x-ray machines.

- Beam quality (HVL):
    Superficial   0.4 - 14 mm Al
    Orthovoltage   0.5 - 4 mm Cu
- Scatter target
- 30 or 50 cm SSD for the orthovoltage units and 15 or 25 cm for the specifically superficial unit
- Dose rate ~0.65-20 Gy/min, depending on the SSD and filtration.
- 250 kVp x-rays are considered the 'gold standard' for radiobiology; RBE for ^{60}Co γ rays is ~ 0.85 that for 250 kVp x-rays

B.   Teletherapy units
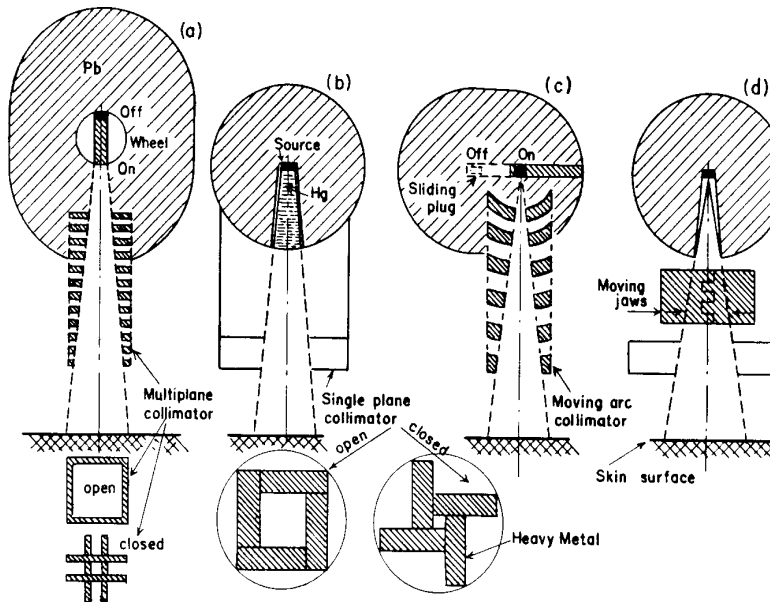
- Source strength typically 10^4 Ci
- dose rate ~240 cGy/min @ 80 SAD. Newer units use a stronger source and operate at 100 cm SAD.
- Leakage in off position: at 100cm, average of 2mR/hr, max of 10 mR/hr.
- Leakage in on position: 0.1% of dose in air at 100cm.
- Trimmers (45 & 55 cm)
- d_{max} ~0.5cm for a 10 x 10 cm^2 field; decreases with increasing field size and decreasing SSD due to electron contamination
- Cobalt 60 units have long been superceded by linear accelerators in the U.S, but ^{60}Co is still used

as a reference standard for dosimetry.
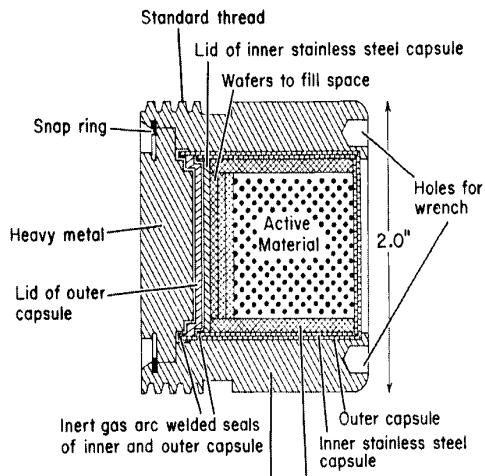
- Source diameter, s, 1.5 - 2 cm;
- Penumbra, p, = s * (F/c-1), where F=SAD and c=source to collimator distance ; p is greater than for linacs because of large source size.
- NRC and State regulations: monthly, annual checks; wipe testing; bookkeeping; radiation survey; five year inspection; quality assurance on patient treatments.

C. Linear accelerators

1. Acceleration principle:

a.   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.

$$V = nv$$

   - 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

   At high energies (> 0.5 MV), it is impractical to use DC voltages to accelerate the electrons and, instead, the principal of repeated application of a constant voltage is used, so that an oscillating form of power supply is needed. Both linear accelerators and cyclic accelerators are based on this principle.
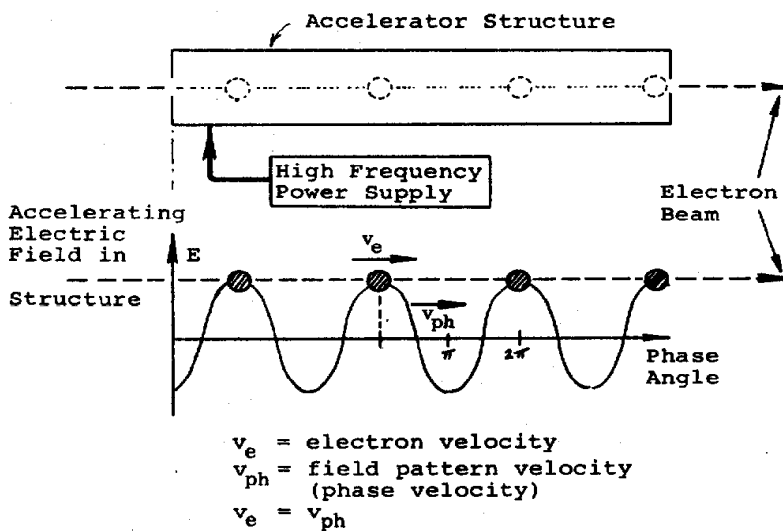
The wavelength has to be short enough to make the accelerators reasonably small. S band microwave technology, developed for radar in WWII, has a frequency of ~3 GHz or λ=10 cm and has been extensively developed for radiation therapy. It is interesting to note, however, that an x-band waveguide (x3 frequency) has recently been developed for medical applications, namely a portable electron-only linear accelerator (< 12 MeV), where a short waveguide is essential.

v_e = electron velocity
v_{ph} = field pattern velocity (phase velocity)
v_e = v_{ph}
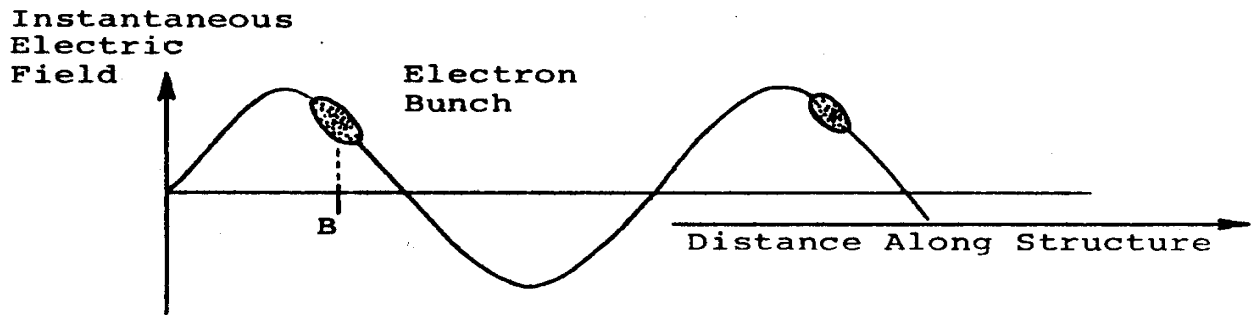
Electrons are accelerated in bunches along an enclosed structure called a waveguide. Electron bunches travelling with the field pattern typically gain energy at the rate of several MeV/m of structure length while the maximum instantaneous potential difference between the internal parts of the accelerator structure does not exceed a few hundred kV and the outside of the structure remains at ground potential.

Electron bunches behave in a phase stable manner: electrons ahead of the bunch B are subjected to a lower field and are therefore retarded back to B; electrons behind the bunch B are subjected to a higher field and are therefore accelerated back to B.
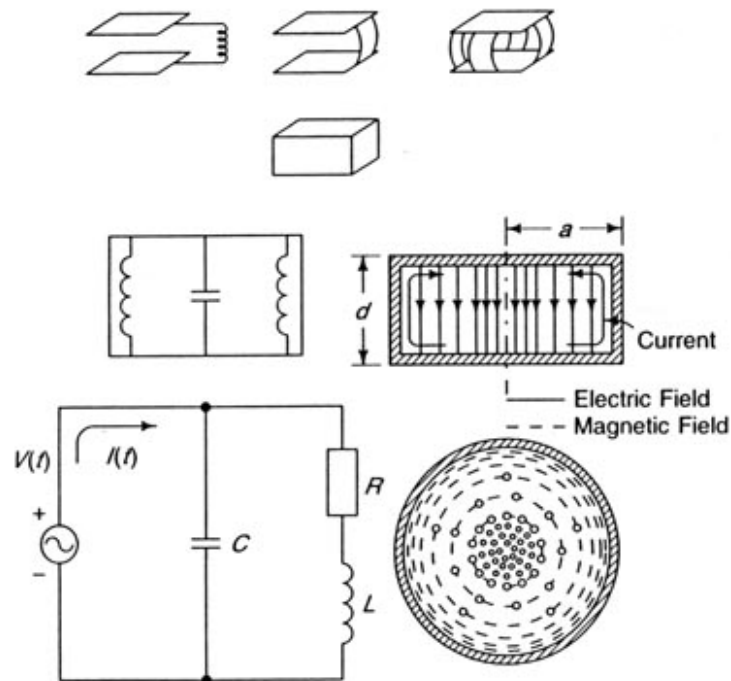
Principle of cavity design:

The sketches opposite show how 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. Thus the capacitor, resistance and inductance shown at the top 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.

3.   Cavity operation:

a.   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

$$Q = \frac{\text{energy stored in cycle}}{\text{energy lost/cycle}}$$
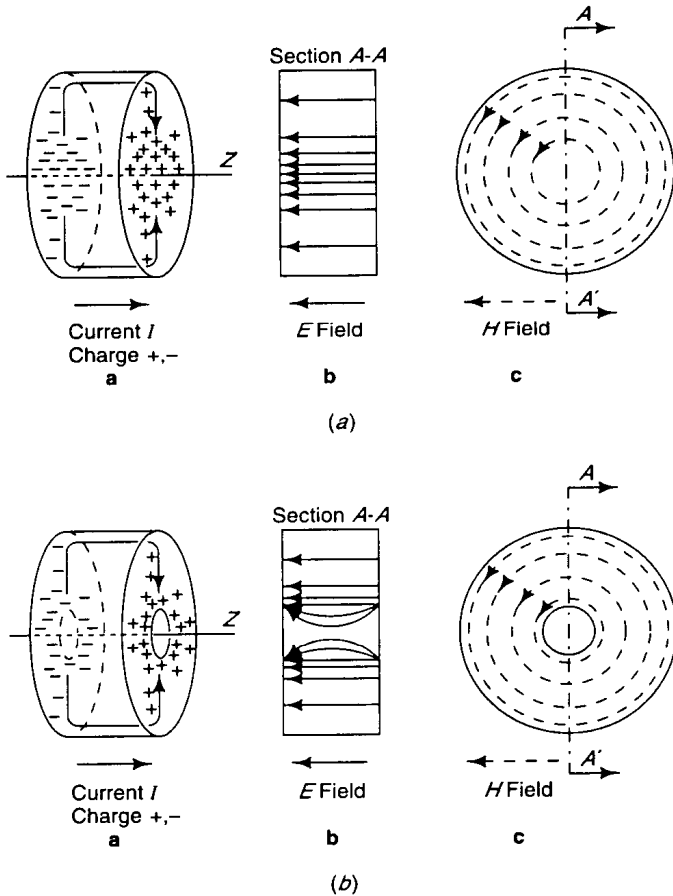
      For a circuit, $Q \sim 10^2$, whereas for a cavity, $Q \sim 10$
   4.   Achieved through devices called magnetrons and klystrons
   5.   To understand these devices, need to consider properties of cavity resonators
   6.   Cavity resonators feature in both power sources and accelerating structures

b.   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

Section A-A

Current I
Charge +,−
a

E Field
b

H Field
c

(a)

Section A-A

Current I
Charge +,−
a

E Field
b

H Field
c

(b)

- The standard technique of resonant circuits using discrete capacitative, resistive and inductive components no longer suffices at a frequency of 3 GHz, because of the extremely small dimensions required and the high energy losses of such systems.
- in general, $\omega=(LC)^{-1/2}$ for a resonant circuit, so one needs very small L and C and hence small dimensions to obtain high frequencies, so ordinary resonant circuits become impractical. This leads to the use of cavities as a form of resonant circuit since they have low L and C.
- electric, magnetic field configurations for lowest resonant mode are shown in the diagrams. Note that only the electric field plays a role in electron acceleration.
- 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, i.e., low energy losses, since for a resonant circuit, $Q \sim 10^2$ (where $Q=f_0/2\Delta f$ and $2\Delta f$ is FWHM), whereas for a cavity, $Q \sim 10^4$

3. RF Power sources:

Generation of high power microwave pulses is achieved through devices called magnetrons and klystrons. Both devices embody the principles of cavity resonators.

a. Klystron
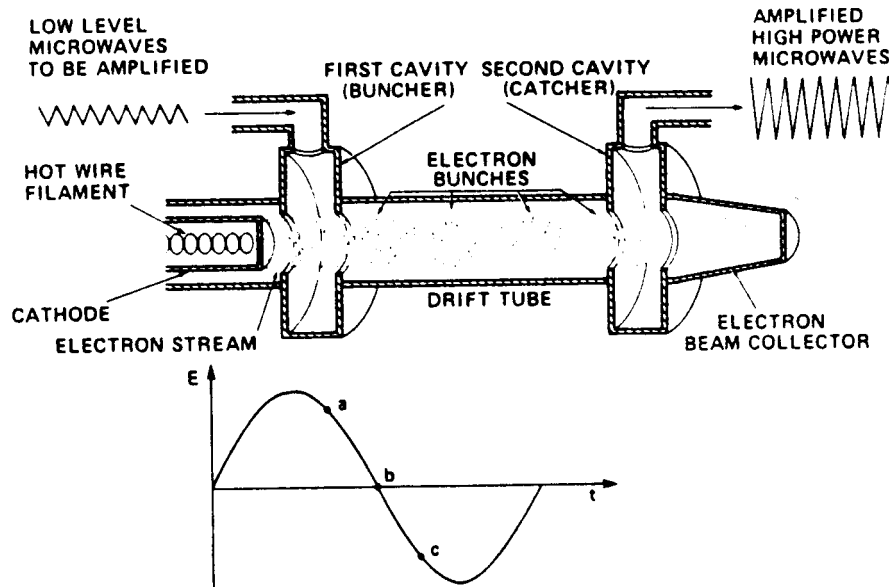
-   acts as a power amplifier
-   suitable for high energy accelerators (> 10 MV)

-   practical units generally have several stages
-   typically 20 MW peak power and 20 kW average power
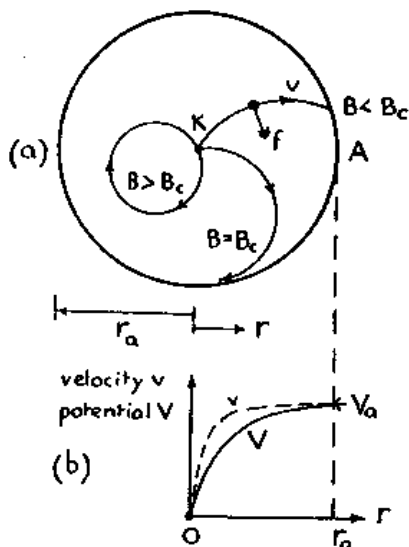
b. Magnetron

Fig. 47.—Illustrating the simple theory of the cylindrical magnetron.

The principle of the magnetron is illustrated in figure 47. A cylindrical anode has the cathode along its axis. A magnetic field is directed along the axis of the cylinder. At low magnetic fields, the electron paths' are bent, but the electrons still reach the anode. At a field Bc, the electron paths' just graze the anode. For higher fields, individual electrons are unable to reach the anode. Figure 48 shows, above, a simplified experimental arrangement and, below, the variation in anode current with magnetic
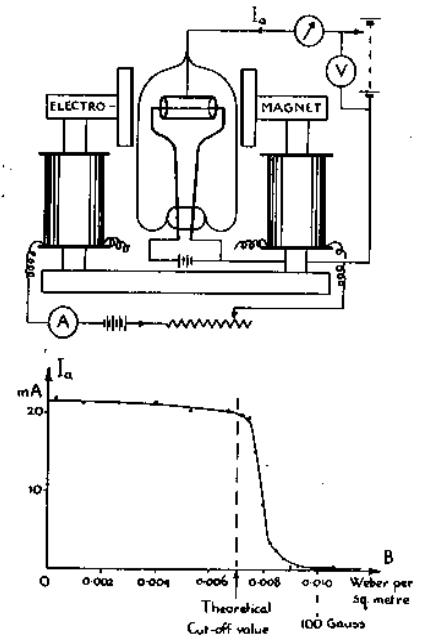
Fig. 48.—The cut-off characteristic of a magnetron, and the apparatus for finding it (Experiment 1).
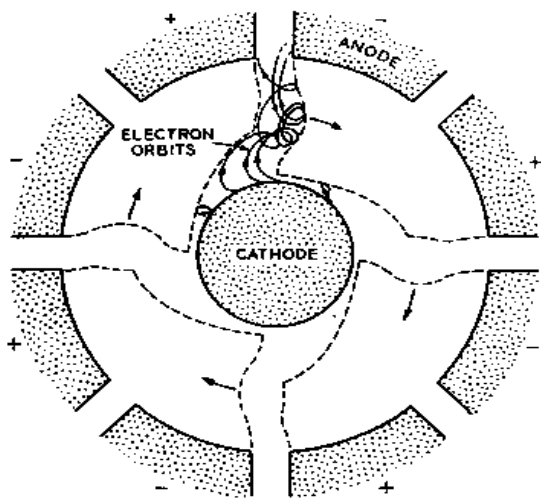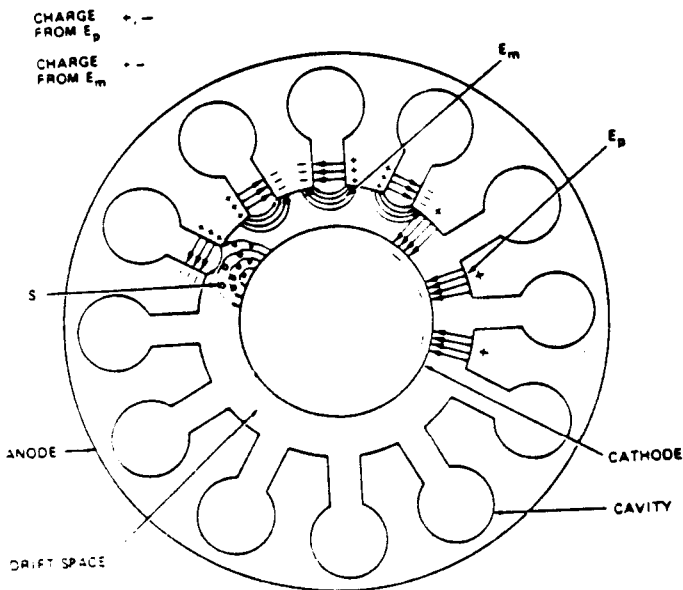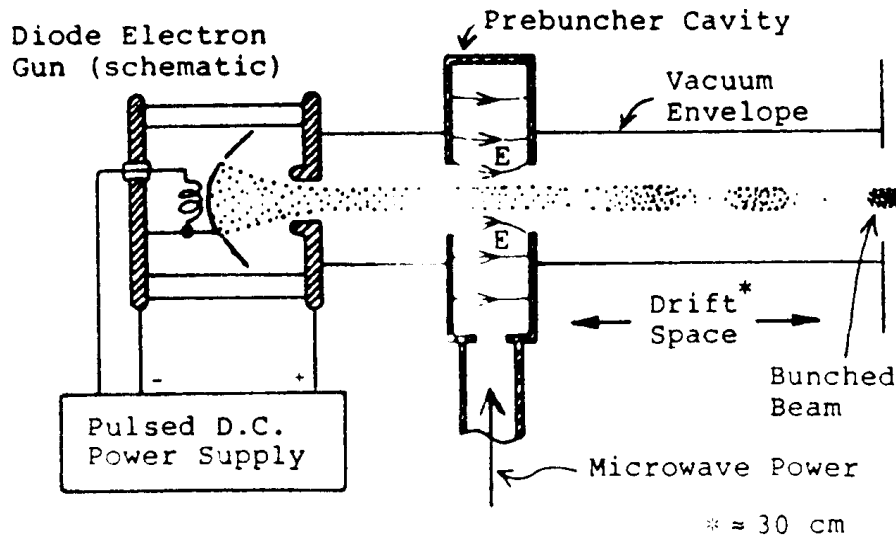
field.

FIG. 326.—Space-charge distribution and electron paths in an 8-cavity magnetron, when oscillating.

Under static conditions, no electrons would reach the anode and there would be a cylindrical space charge of diameter less than the inner diameter of the anode. This space charge would, in effect, circulate around the cathode with an angular velocity depending on the anode potential and the magnetic flux density. However, the circulating electrons induce a charge distribution between adjacent segments of the anode in a manner similar to that in the catcher cavity of the klystron and an electric field of microwave frequency. This, in turn, perturbs the electron orbits so that the space charge distribution into a form resembling the spokes of a wheel. The electrons interact with the electric fields generated in these gaps and, under certain conditions, the resonant cavities gain energy from the orbiting electrons which are slowed and eventually spiral into the anode, leading to anode current.
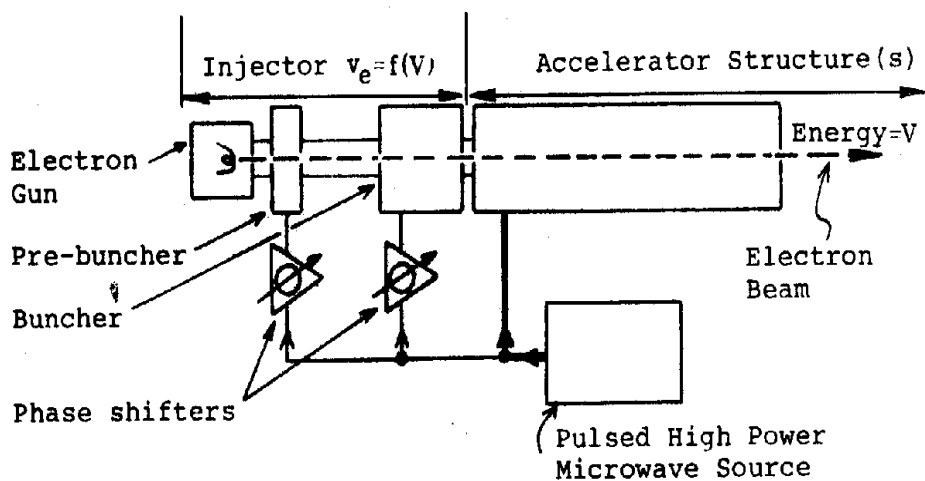

- cross section through 12 cavity magnetron
- magnetic field is applied perpendicular to the paper, along the axis of the cavity
- acts as a high power oscillator
- suitable for low energy accelerators (4, 6 MV)
- more unstable than klystron
- typically 2-3 MW peak power
- average lifetime ~ 1 yr
  (can be extended by running at a lower dose rate)

4. Electron gun:

Diode Electron
Gun (schematic)

Prebuncher Cavity

Vacuum
Envelope

E

E

Drift*
Space

Bunched
Beam

Pulsed D.C.
Power Supply

Microwave Power

* ≈ 30 cm

-   Schematic of
    electron source
    (gun) and
    prebuncher cavity

5. Accelerator layout:

Injector $v_e = f(V)$

Accelerator Structure(s)

Energy=V

Electron
Gun

Pre-buncher

Buncher

Phase shifters

Electron
Beam

Pulsed High Power
Microwave Source

Schematic of accelerator
components, including:
-   electron gun
-   prebuncher cavity
-   buncher cavity
-   accelerating guide
Note that in the injector
section, the velocity of the
electron varies as its energy
increases while in the
accelerator section it is
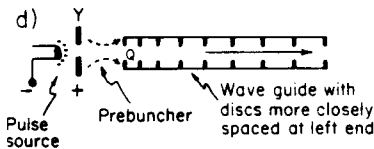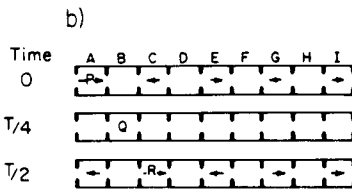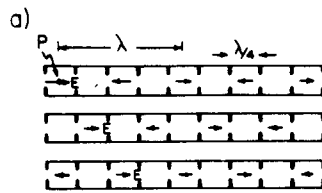essentially constant.

6. Accelerator waveguide:
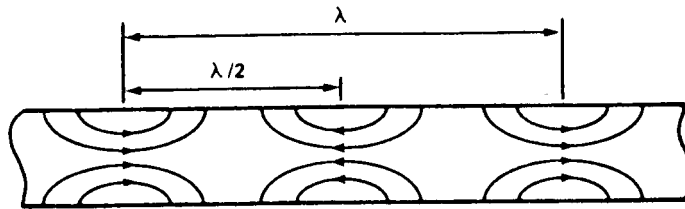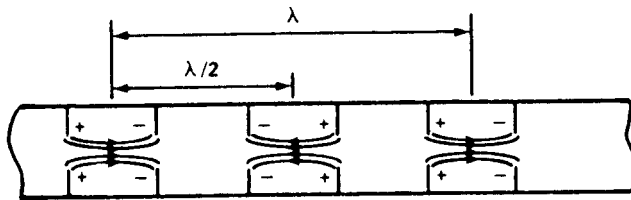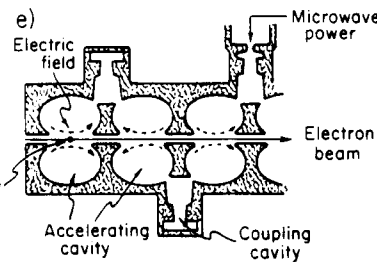
- Electric field distribution from RF source in uniform cylinder
- The phase velocity of such an arrangement is > c and so cannot be used to accelerate electrons

- Electric field from RF source in disc loaded cavity to slow down electric field to ensure that the electrons can stay in phase with the EM wave.

- Principle of (a) travelling wave and (b) standing wave acceleration at three different times.
- (c) shows the principle of the electron bunch in phase with the EM field
- The prebuncher section in (d) shows schematically the unequal spacing of discs to account for change in velocity with energy
- Note that, unlike the travelling wave system, alternate cavities never have an electric field across the gap. Eliminating these cavities by means of the side coupled arrangement (Los Alamos model) shown in (e) provides a shorter waveguide
- Note that while the waveguide is under high vacuum, the RF guide contains SF6 gas (previously freon) to prevent electrical breakdown, so a ceramic vacuum coupler has to be used between the two systems

7.   Beam Loading
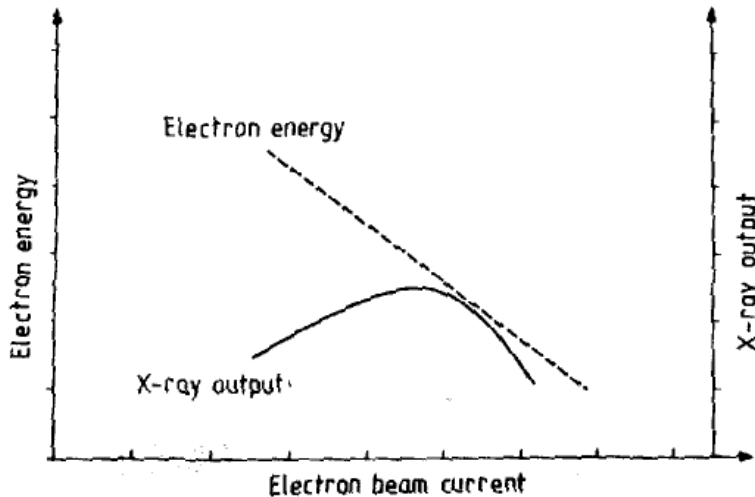
Since the electron beam in the waveguide gains energy from the RF field, it follows that for a fixed microwave power level, the more energy the electron beam gains, the lower the current. Conversely, at low energies, the current can be much higher since less power is required to accelerate the electrons. This is known as the load line (dashed line in figure) for the waveguide. Its exact shape depends on the guide design and the power applied. However, since x-ray production increases with energy, the x-ray output from the machine displays the form shown by the solid line in the figure with a maximum output at a particular energy. This is the normal operating energy for x-rays. If a different energy is selected, the output will be lower (see section 11).

8.   Main power supply and modulator
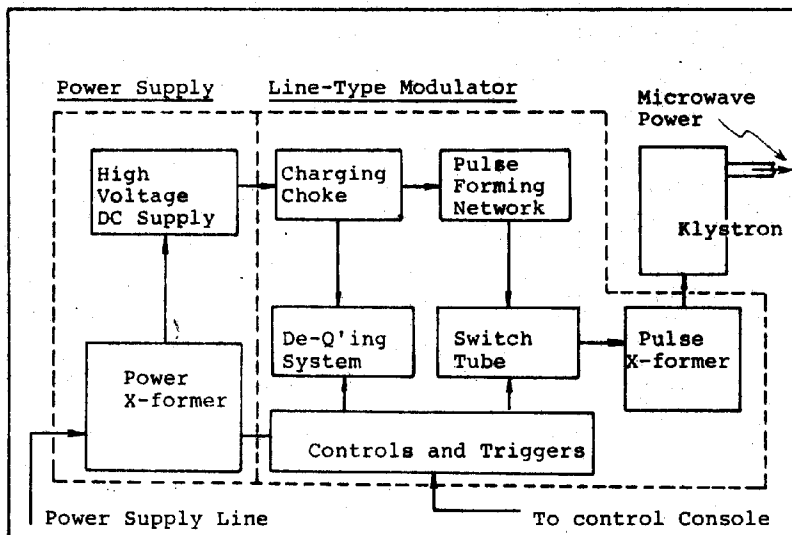
The main power supply is a conventional high-voltage, high-current power supply which charges the pulse forming network (PFN) of the modulator during each inter-pulse period. The PFN is discharged through the primary winding of a pulse transformer by a high power thyratron and delivers high-voltage, high-current pulses to the klystron or magnetron (and sometimes to the electron gun) connected to the winding(s) of the pulse transformer. The length of the high voltage pulse is fixed by the parameters of the PFN. However, the length of the RF pulse produced by a high power klystron can be changed by altering the length of the RF drive pulse. Similar control of the magnetron oscillator RF pulse length is obviously not possible.

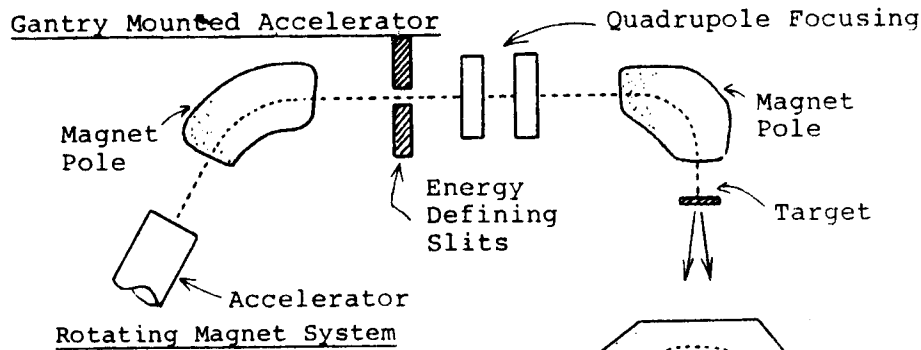9. Low vs. medium/high energy linear accelerators:
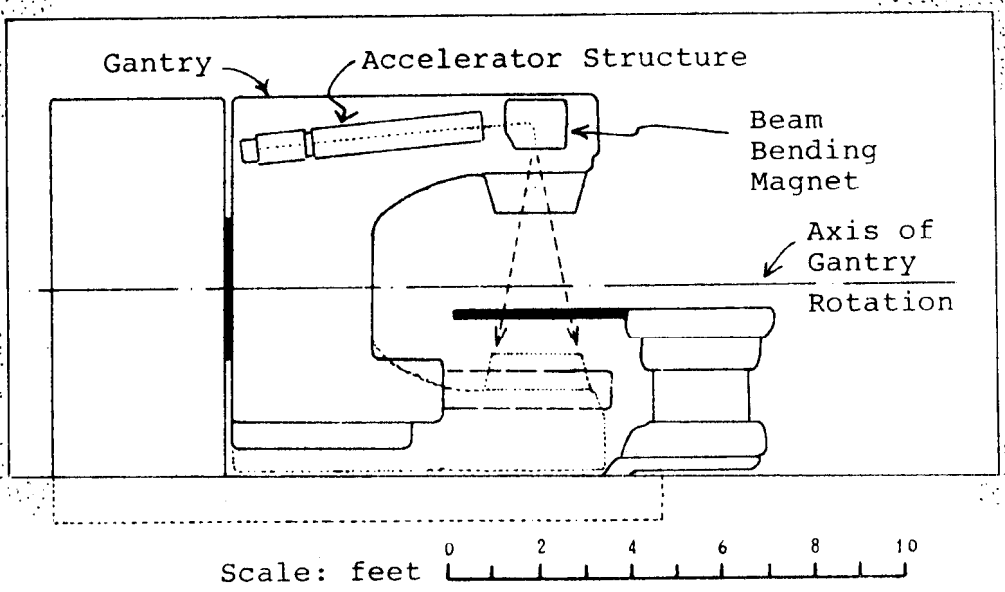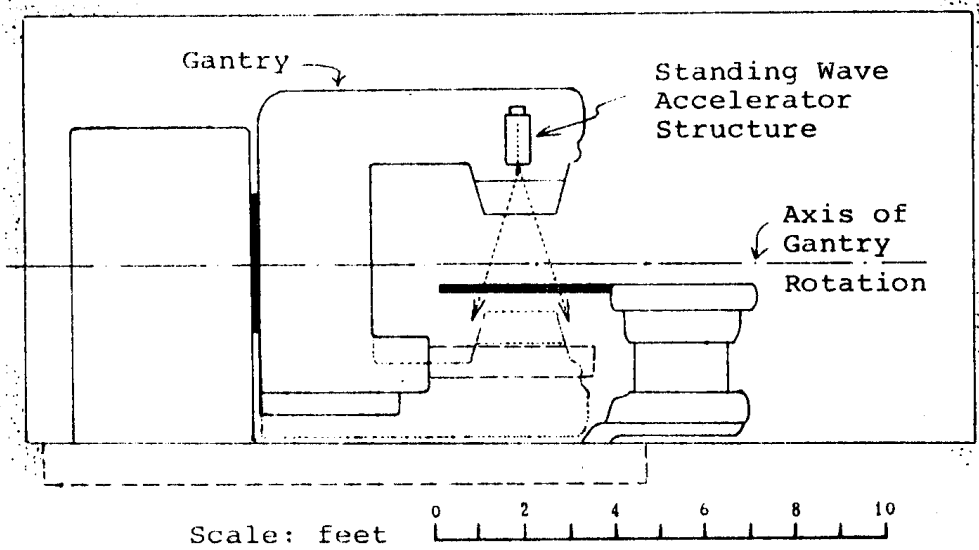
The upper diagram shows the short waveguide of a low energy linear accelerator pointing directly towards the target. It is possible to accommodate the guide in this direction and still maintain a floor to isocenter height that is acceptable to therapists. For a medium/high energy linear accelerator, however, this is not possible and the waveguide is aligned parallel to the gantry rotation axis. A 270° magnet bends the beam onto the target. The low energy machine does not require this magnet and therefore has a larger energy spread than the machine with the magnet (typically ±3% using slits).

10. Magnet systems:

90° Magnet

Magnet Pole

Electron Beam

Electron Beam

270° Magnet

Target

b a c

c
a
b
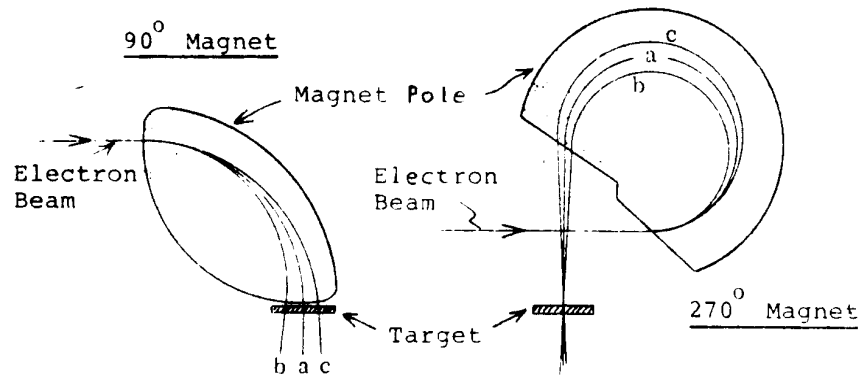
- Principle of 270° bending magnet (Enge). Note the achromatic focus vs. a dispersed focus for the 90° magnet.

Gantry Mounted Accelerator

Quadrupole Focusing

Magnet Pole

Magnet Pole

Energy Defining Slits

Target

Accelerator

Rotating Magnet System

Quadrupole Focusing Magnets

Target

Slits

Non-uniform Field Magnet

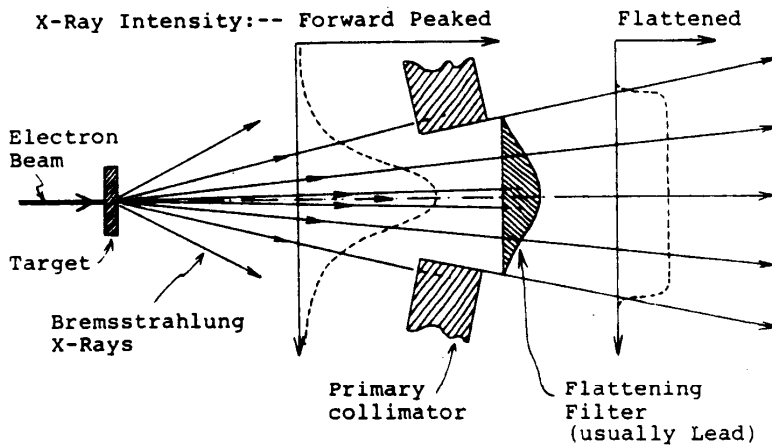Achromatic Three Magnet System

Rotating Vacuum Joint

- alternative, more complicated bending techniques, using quadrupoles and/or additional bending magnets, to achieve an achromatic focus
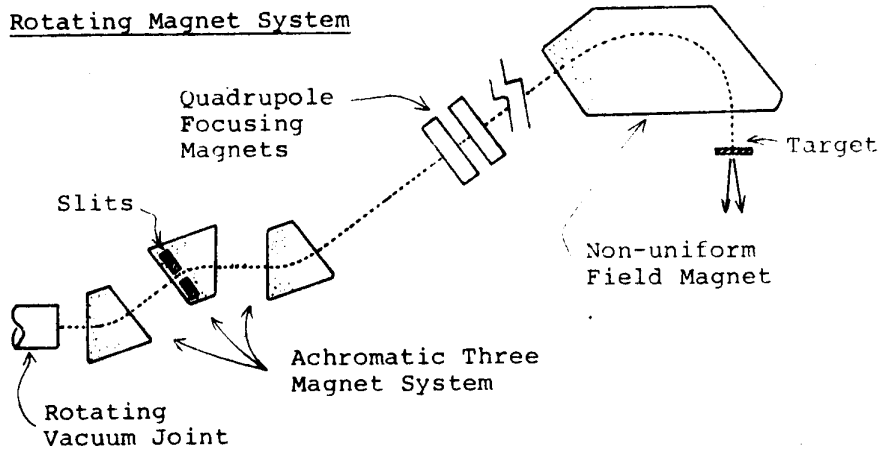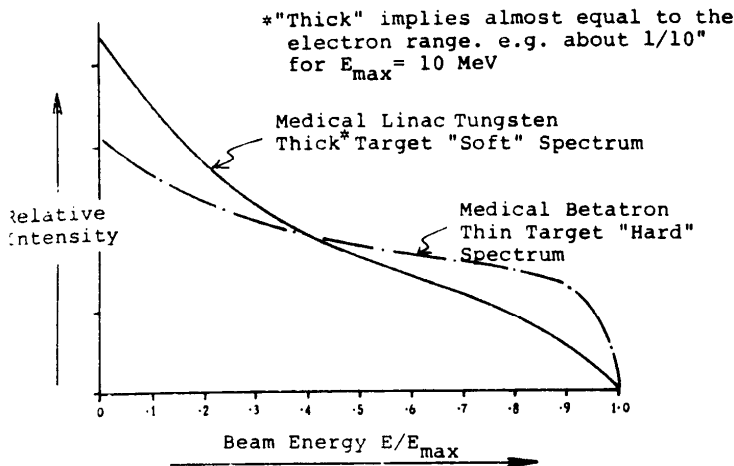
11. Target and flattening filter:

- a flattening filter is used to obtain a broad beam for clinical use. High Z materials are usually used at low energies and intermediate Z values at high energies.


- Comparison between the energy spectra for linear accelerators ('thick' target) and betatrons ('thin' target). Not the higher proportion of high energy photons for the betatron spectrum.
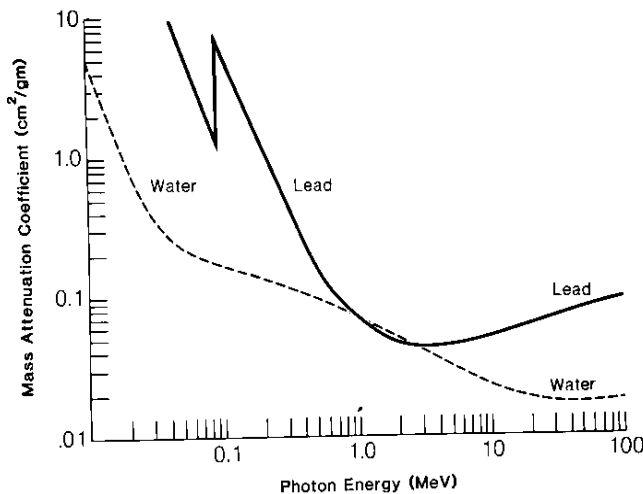

- The mass attenuation coefficient graph shows that the minimum value for lead is around 2 MV (the rise at higher energies is due to pair production). Thus, for high energy beams (>10 MV), a flattening filter made of this material will soften the beam. For lower Z materials, such as iron, this minimum is

higher and there is no beam softening at high energies.

## 12.   Photon/electron beam delivery systems:
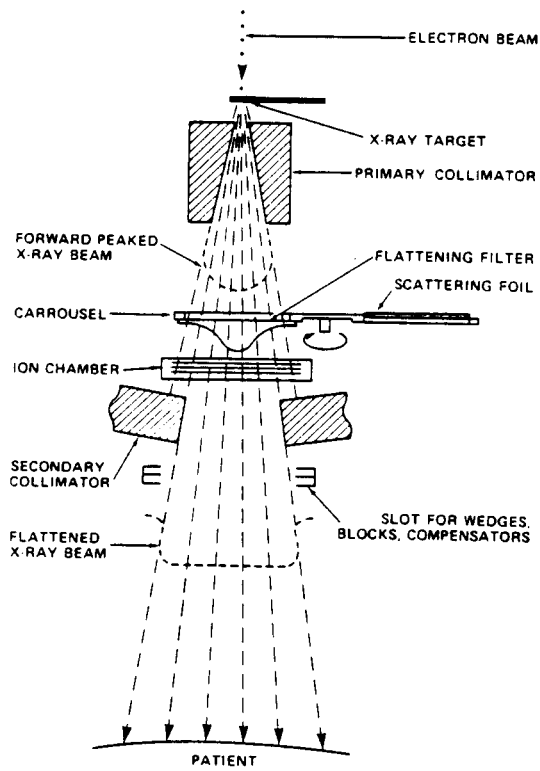
-    schematic representation of a clinical x-ray beam showing the target, primary collimator, flattening filter, ion chamber and secondary collimators.
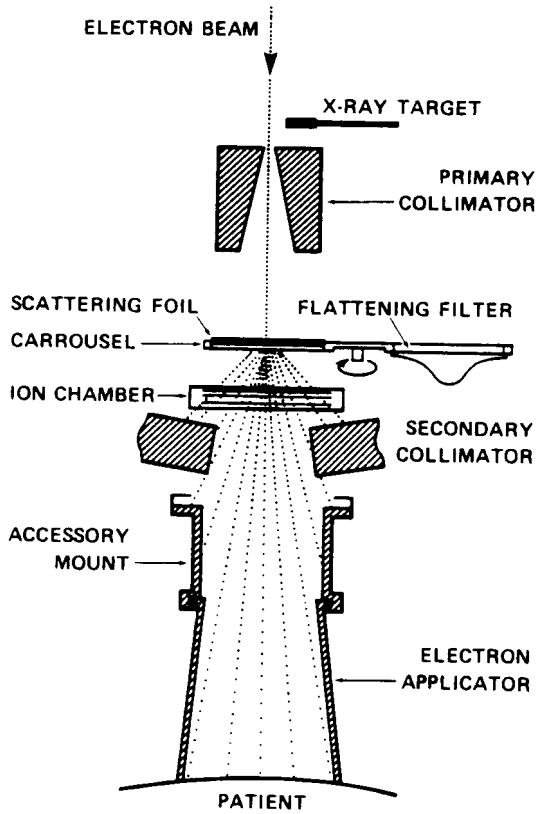
- schematic representation of a clinical electron beam showing the x-ray target and flattening filter withdrawn, the scattering foils in place and the electron applicator to provide a sharp penumbra. Note that because flattening filters are not used in electron beam production, the amount of internal electron beam current is 20-100 x lower than for photon beams.

13. Electron linear accelerators with dual-energy photon beams:
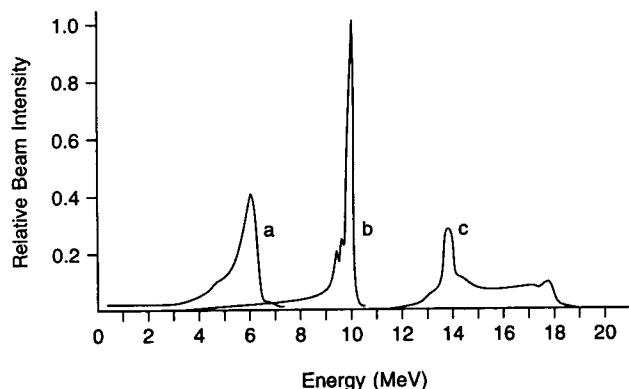
Beam Loading: a, heavy; b, optimal; c, light

High-energy linear accelerators are available with two photon energies. While this is not a new idea (the Clinac 35, a travelling wave machine was designed for two energies in the late 60's), for many years it was relatively uncommon. The chief problem with the design of such a machine is achieving a "respectable" dose rate at the two, usually widely different, energies (see figure). The problem goes back to the "load line" where it can be seen that a waveguide can be optimized for maximum output at one photon energy, so that at the other energy, the output is generally low, an undesirable feature for conformal therapy applications.

In the travelling wave machine, a high dose rate at both energies is achieved by having two independent accelerator sections to the waveguide. The power and phase of the RF to the waveguide is adjusted between the two sections to achieve the optimal efficiency at both energies. For the standing waveguide, there are four options (see table), only two of which are simple, requiring only a change in the operating characteristics (power level etc.), neither of which leads to two beam energies with optimal performance. The other two options require machines of a different design of the machine and are therefore complex solutions.

| Method	Structure	Advantage	Disadvantage
Vary RF power and/or beam loading	Single section	Simple	Rapid spectrum deterioration
Detune RF signal and/or accelerator cavity	Single section	Simple	Unstable and limited range
Combination of two accelerators with phase shifter and attenuator	Two section	Energy variable in wide range	Complex
Combination of single accelerator with 180° bend magnet	Single section but double path	High energy gain per given RF power	Complex and limited range
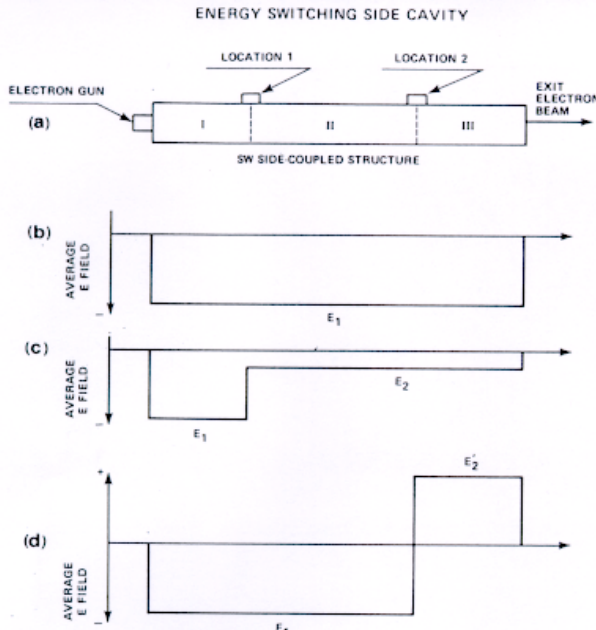
FIG. 15. Energy switching side-coupled SW structure and average E field distributions for operating conditions described in the text.

A novel idea has been introduced for the standing wave machine where one of the side coupled cavities is modified to vary the magnitude or sign of the accelerating fields of the adjacent centerline cavities by changing the RF coupling between the cavities. This is a so-called energy switch. There are two ways this switch can be used. In the first case, one can produce a step in the magnitude of the accelerating field of the structure while maintaining the resonant condition (electrons in phase with RF field). Alternatively one can completely close the switch and reverse the phase of the RF field to decelerate the electrons. Figure 15a shows a sketch of a conventional accelerating SW waveguide with two possible locations for the energy switch. Figure 15b shows the conventional acceleration mode with no switch in place and with a constant electric field amplitude along the guide; the terminal energy is proportional to the area under the rectangle E_1. In Fig 15c, the amplitude of the electric field is reduced by inserting the plunger at location #1 so that the electric field changes from E_1 to E_2. The terminal energy is represented by the sum of the areas under E_1 and E_2. Note that the phase is constant throughout the guide. Finally, in Fig 15d, the switch is placed at location #2 and fully inserted. This has the effect of reversing the phase by 180° but preserving the amplitude, thus decelerating the electrons. The terminal energy is now represented by the area under E_1 minus that under E_2.
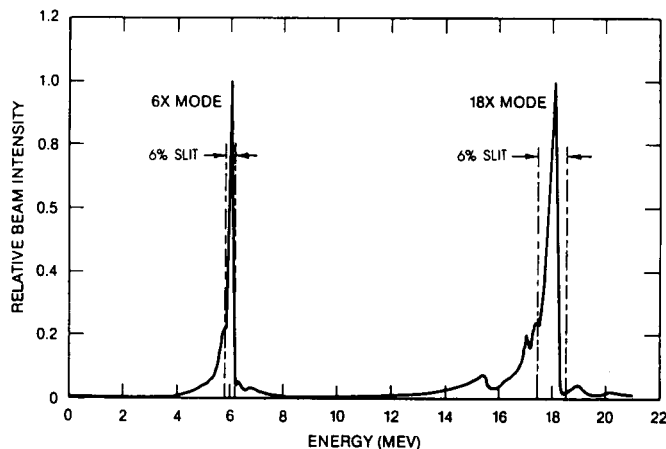

The result is that equally high beam intensities can be achieved at widely separated energies.

14.   Neutron background:
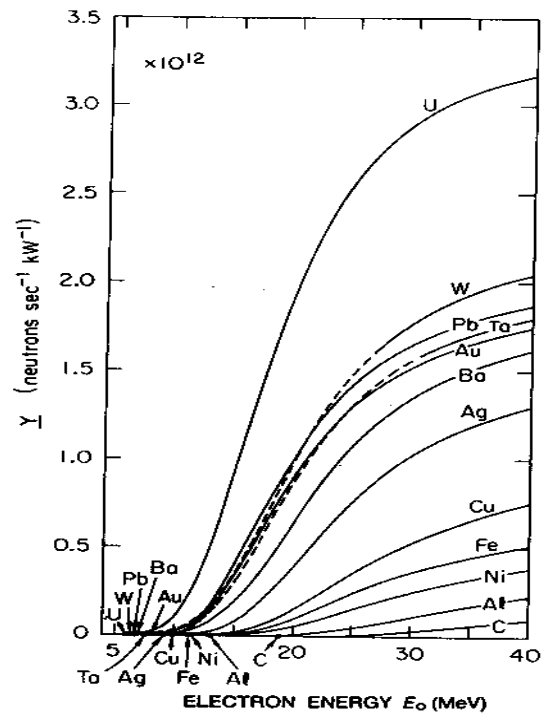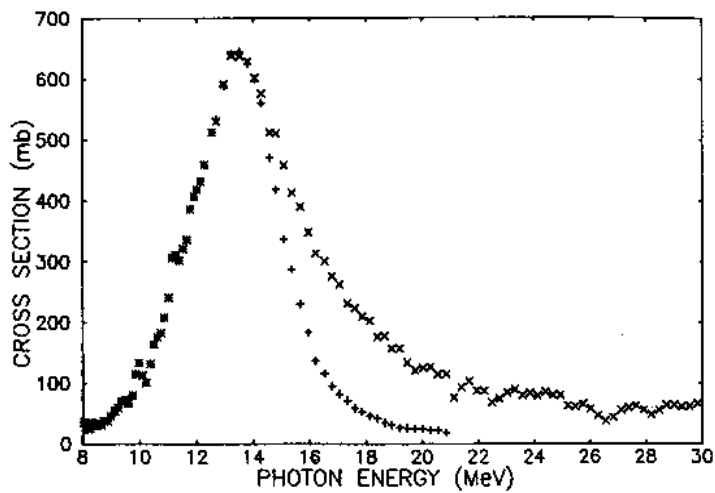
Neutrons are an inevitable byproduct of high energy electron accelerators. For electron energies greater than 8 MeV on target, neutrons will be produced in the high Z materials in the head, notably in lead and in tungsten, although significant neutron production only occurs at energies of 15 MeV or higher.


"Out-of-Beam" Data
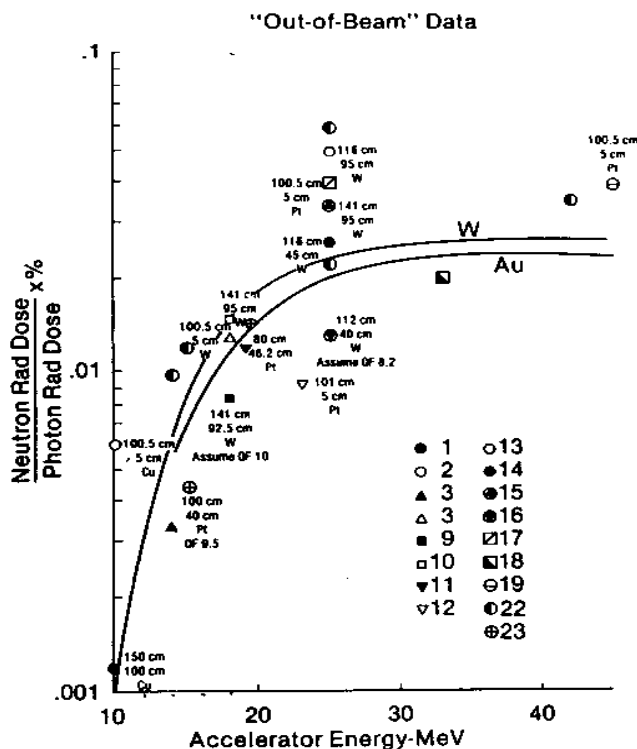
The neutron leakage from machines with various x-ray energies was compiled by Almond; the data showed that for high energies the leakage at high energies was 0.5% Sv/Gy in the beam and 0.2% Sv/Gy outside the beam.
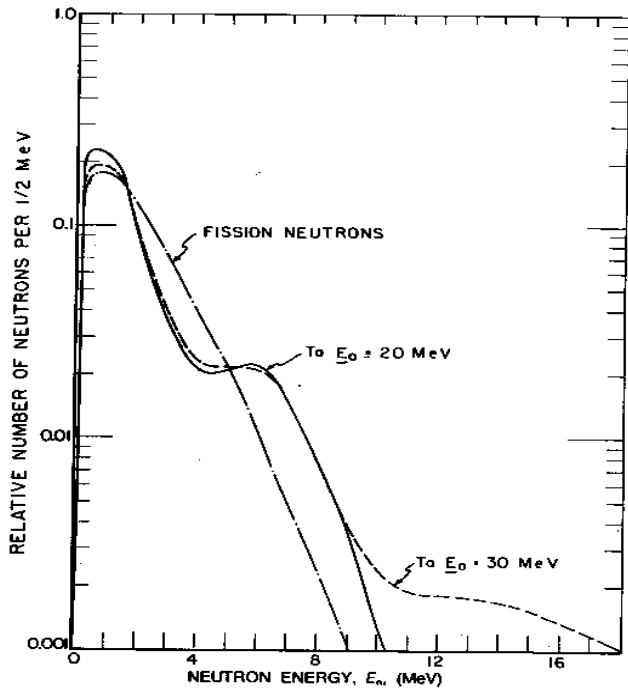
The energy spectrum is very similar to that of fission neutrons, with a most probable energy of ~ 1 MeV, falling approximately exponentially at higher energies. At these energies, tungsten is a more effective material for reducing the energy of the neutrons than lead per cm of material.
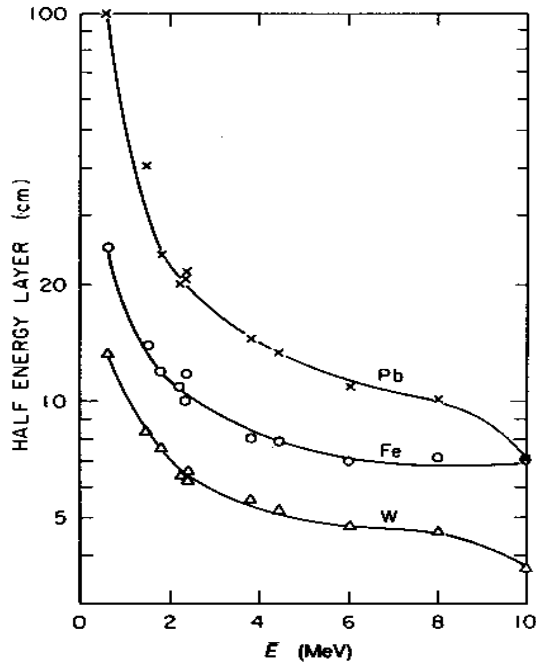
Neutrons with energies below 2 MeV are very poorly attenuated by lead, but less so by iron and tungsten. Curves of the half energy thickness, or the thickness to reduce the energy by one half, increase very rapidly as the neutron energy goes below 1 MeV. Unfortunately, these are the typical neutron energies from high energy linear accelerators.

15. Other physical characteristics of linear accelerators:

- Compromise between flatness for small and large fields with single flattening filter
- Photon characteristics: d_{max} vs. energy,

$\sim$ 3mm beam spot; smaller penumbra vs. ^{60}Co
- Electron beams: Profile shaping applicators, scanning beams; scanning beams have lower bremsstrahlung background at high energies
- Dose rates: 4 & 6 MV machines - 250 cGy/min, now up to 600 cGy/min

High energy, dual energy machines - 100-600 cGy/min
- Neutrons: Threshold at $\sim$10 MV, plateau at $\sim$20-25 MV
- Dual Dose monitoring system plus check cycle for safety


16. Features of computer controlled linear accelerators:

- multileaf collimators

Leaf resolution is generally 1 cm at isocenter, but now units are available with 0.5 cm resolution for small fields. Micro-MLCs have a resolution of 4 mm.
- dynamic wedges
- beam intensity modulation
- better handling of beam diagnostics, locally and remotely

D.   Properties of megavoltage x-ray beams

1. Percent depth dose curves

As seen earlier, the x-ray spectrum from linear accelerators is a bremstrahlung spectrum. That means that there are relatively few photons near the peak energy compared with at lower energies. A rule of thumb, developed in the early days of linear accelerators was that the average energy was 1/3 of the peak energy, but this is only approximately true at high energies. Monte Carlo studies of primary bremsstrahlung spectra indicate average photon energies of 1.76, 2.55 and 4.75 for 6, 10 and 25 MV x-ray beams respectively. Unlike orthovoltage x-rays, the maximum dose occurs at depth, not at the surface. This depth of maximum dose depends on both the maximum photon energy and the field size of the beam.
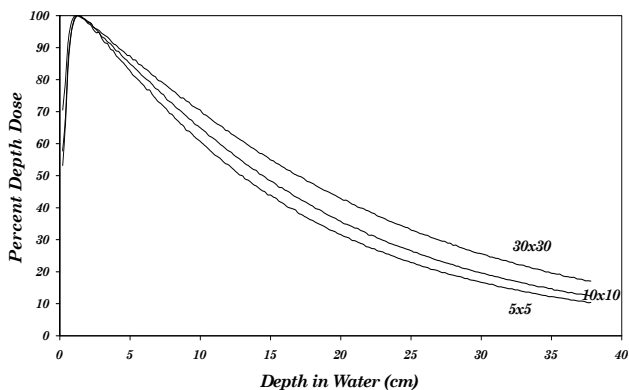
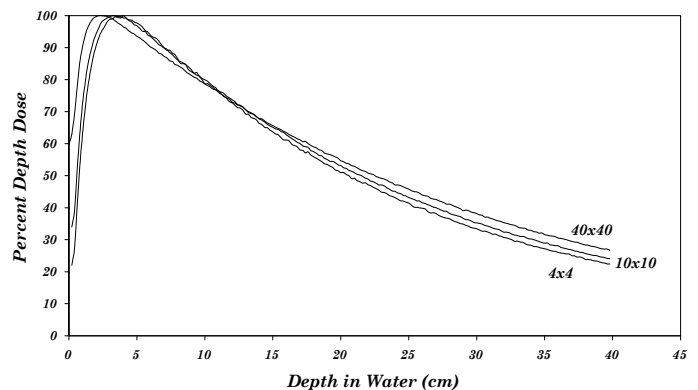*Variation of Percent Depth Dose with Energy*
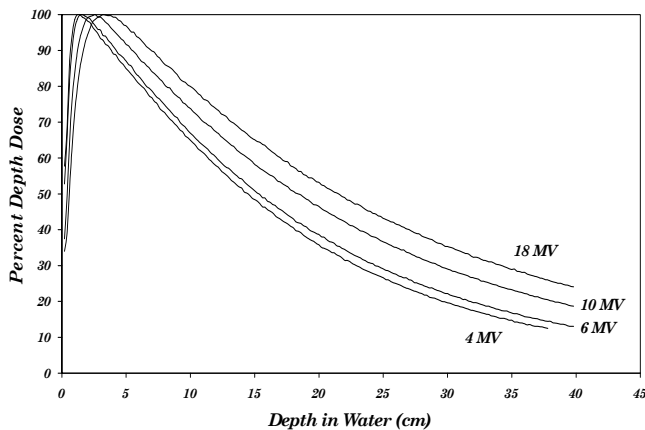
a. Energy dependence: The depth of maximum dose increases with energy, but not linearly. This non-linearity is probably related to contribution from electrons generated in the head skewing the depth dose curve. Depth dose curves for 4, 6, 10 and 18 MV are shown in the curve above. At 4 MV, the depth is about 1 cm, whereas for 18 MV it is closer to 3.5 cm.

b. Field size dependence: The depth of maximum dose decreases with field size due to contamination from electrons generated in the head. This is more severe for the high energy than for low energy beams. This is illustrated in the curves shown below for 4 MV and 18 MV.
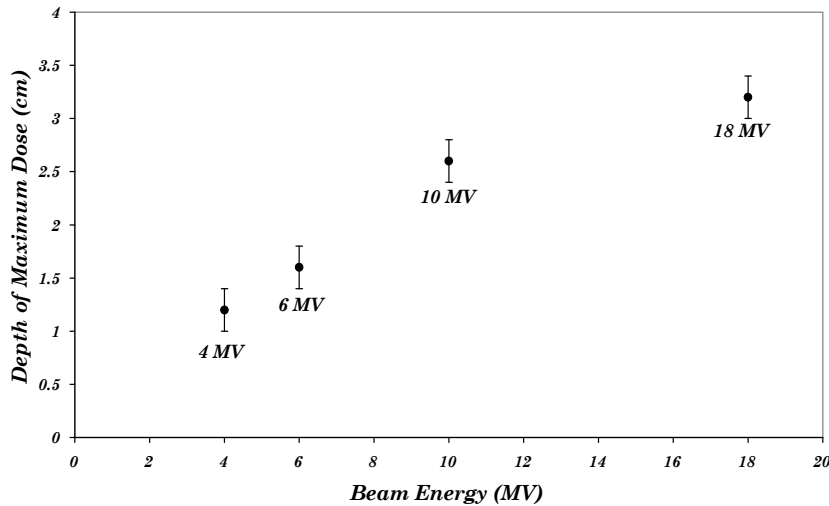
Variation of Percent Depth Dose at Field Size for 4 MV Photons

*Variation of Percent Depth Dose at Field Size for 18 MV Photons*

Variation of Maximum Depth Dose with Energy

c. Depth of maximum dose:

The variation of the depth of maximum dose, d_{max}, with energy is shown for 4, 6, 10 and 18 MV, illustrating the range in d_{max} and its non-linearity with energy. The error bars indicate 2 mm uncertainty on the measurements.

Variation of Depth of Maximum Dose wth Field Size
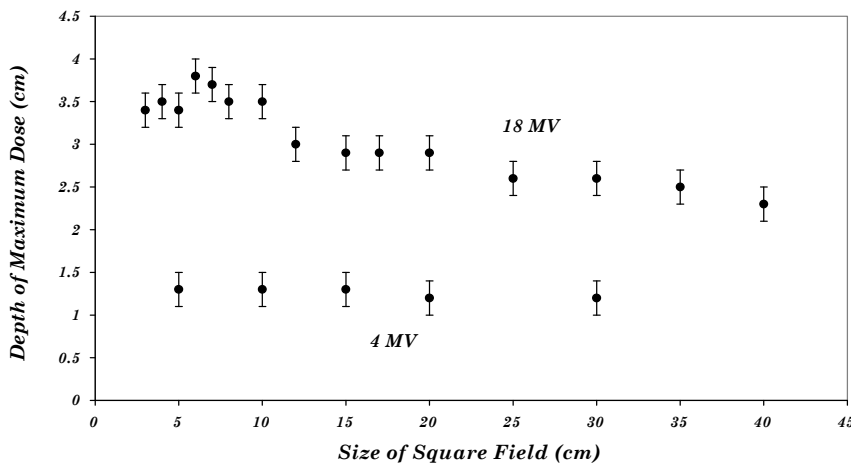
This plot shows more clearly that there is a greater variation of d_{max} with field size at high energies than at low energies. At 18 MV, for example, d_{max} varies from about 3.5 cm at small field sizes to almost 2.5 for large field sizes. In contrast, the variation at 4 MV is barely perceptible and amounts to no more than 1 mm.
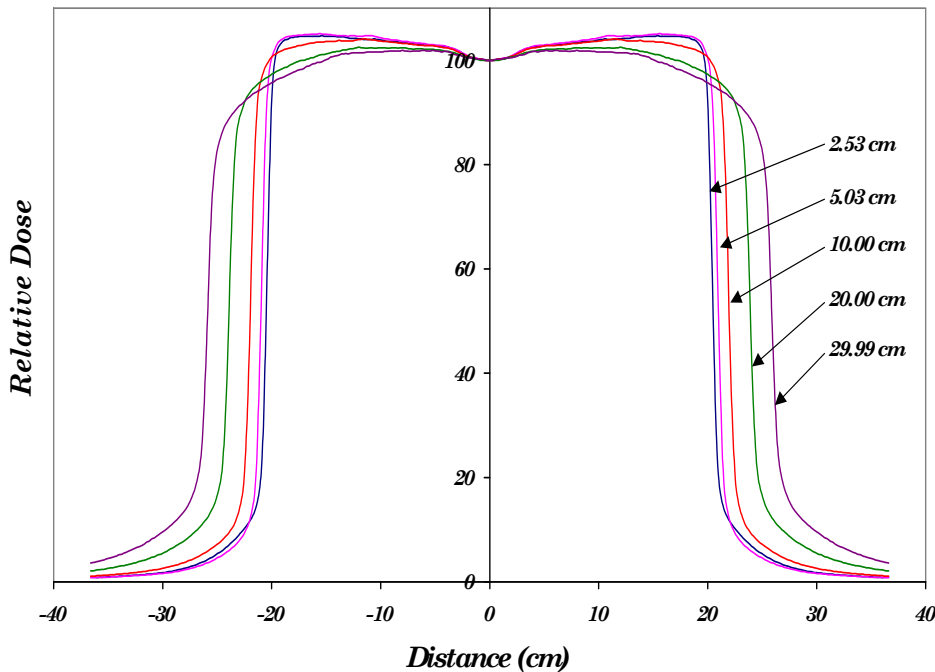
d. Surface dose: The surface dose varies with energy, field size and accessory placement, such as a wedge of blocking tray. In general, the surface dose increases with all these parameters due to electron contamination. The surface dose also increases with decreasing SSD for the same reason.

However, different machines having the same energy may have a different surface dose due to different head design.
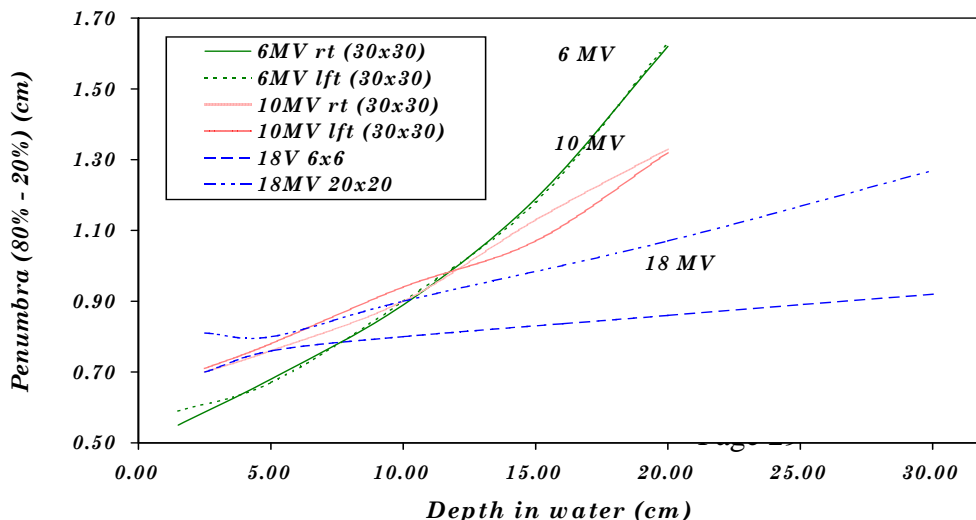
2. Penumbra

Beam penumbra is variously defined in terms of the steepness of the dose distribution at the edge of the beam profile. Typically the distance between the 80% dose (normalized to the

100% on the central axis) and the 20% dose is chosen. A set of beam profiles is shown in the figure for 18 MV x-rays. Note that the curves become more rounded and the penumbra larger as the depth in the phantom increases.

Beam Profiles for a 40x40 Field at 18 MV

Variation of Penumbra with Depth for 6, 10 and 18 MV X-Rays

In the figure shown here, the penumbra for 6, 10 and 18 MV x-

rays is shown as a function of depth in water. It can be seen that the penumbra increases with depth, as might be expected form the increase in photons scattered out of the beam. It also decreases with increasing energy and field size.

References

Ford J.C. Advances in accelerator design. AAPM, Medical Physics Monograph #15.

Johns H.E. and Cunningham J.R. The physics of radiology. C.C.Thomas, Springfield, Illinois. Fourth edition, 1983.

Karzmark C.J. Advances in linear accelerator design for radiotherapy. Med. Phys. 11;105-128, 1984.

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, December 1981

Karzmark C.J. and Pering N.C. Electron linear accelerators for radiation therapy: history, principles and contemporary developments. Phys. Med. Biol. 18;321-354, 1973

Khan F.M. The physics of radiation therapy. Williams and Wilkins. Baltimore, MD. Second edition, 1994

Klevenhagen S.C. Physics of electron beam therapy. Adam Hilger Ltd. Bristol (UK) and Boston. First edition, 1985.

NBS Special Publication 554. Proceedings of a conference on neutrons from electron medical accelerators. U.S. department of Commerce, National Bureau of Standards (Now NIST), Gaithersburg, MD, 1979

NCRP Report No. 79 Neutron contamination from medical electron accelerators. National Council on Radiation Protection and Measurements, Bethesda, MD, 1984

The use of electron linear accelerators in medical radiation therapy: physical characteristics. U.S. Department of Commerce, National Technical Information Service, PB-253-605,1976

Podgorsak, Metcalfe and Van Dyk in 'The Modern Technology in Radiation Oncology, chapter 11, p. 349-435, Medical Phgysics Publishing, Madison, WI, 1999

WSA, Incorporated. The use of electron linear accelerators in medical radiation therapy: physical characteristics. DHEW PUBL (FDA) 76/8027 February, 1976.

More detailed books:

Greene D. Linear accelerators for radiation therapy. Adam Hilger Ltd. Bristol (UK) and Boston. First edition, 1986.

Karzmark C.J., Nunan C.S. and Tanabe E. Medical electron accelerators. McGraw-Hill, New York, NY. First edition, 1993.

Livingood. Cyclic accelerators

Livingston. High energy accelerators

Livingston and Blewett. Particle accelerators, McGraw-Hill, New York, 1962

Persico, Ferrari and Segre. Principles of particle accelerators.

Scharf W.F. Biomedical Particle accelerators. AIP Press, New York, NY. First edition, 1994

Segre, G. Nuclei and particles