CHAPTER 4:
HIGH ENERGY X-RAY GENERATORS:
LINEAR ACCELERATORS

Jason Matney, MS, PhD

Objectives

- Medical electron linear accelerators (often shortened to LINAC)
  - The Basics
  - Power Supply
    - Magnetron/Klystron
  - Accelerator structure
    - Standing-Wave/Traveling Wave
  - X-Ray vs. e- Therapy Modes

Remember Bremsstrahlung Production?

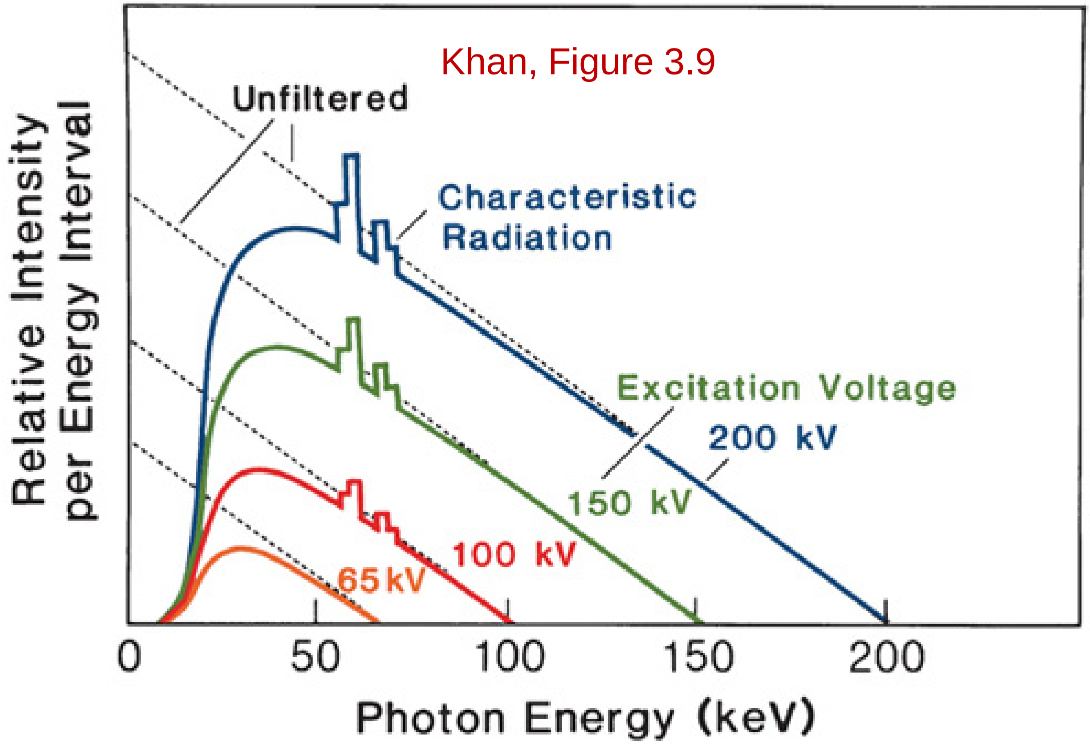
- Electrons are released from cathode and travel to the anode, accelerated in route and attain K.E. as they drop through the potential difference.

  - As the e- passes in the vicinity of positively charged target all or part of the electron’s energy is dissociated from it and propagates in space as EM radiation

X-ray Energy ranges from 0-KvP (max accelerating potential)

Why do we need a LINAC?

- Range of X-ray Energy 0-KvP (max accelerating potential).



If you want higher energy X-rays…You need to hit the target with <u>“faster”</u> electrons → This is the purpose of the accelerator

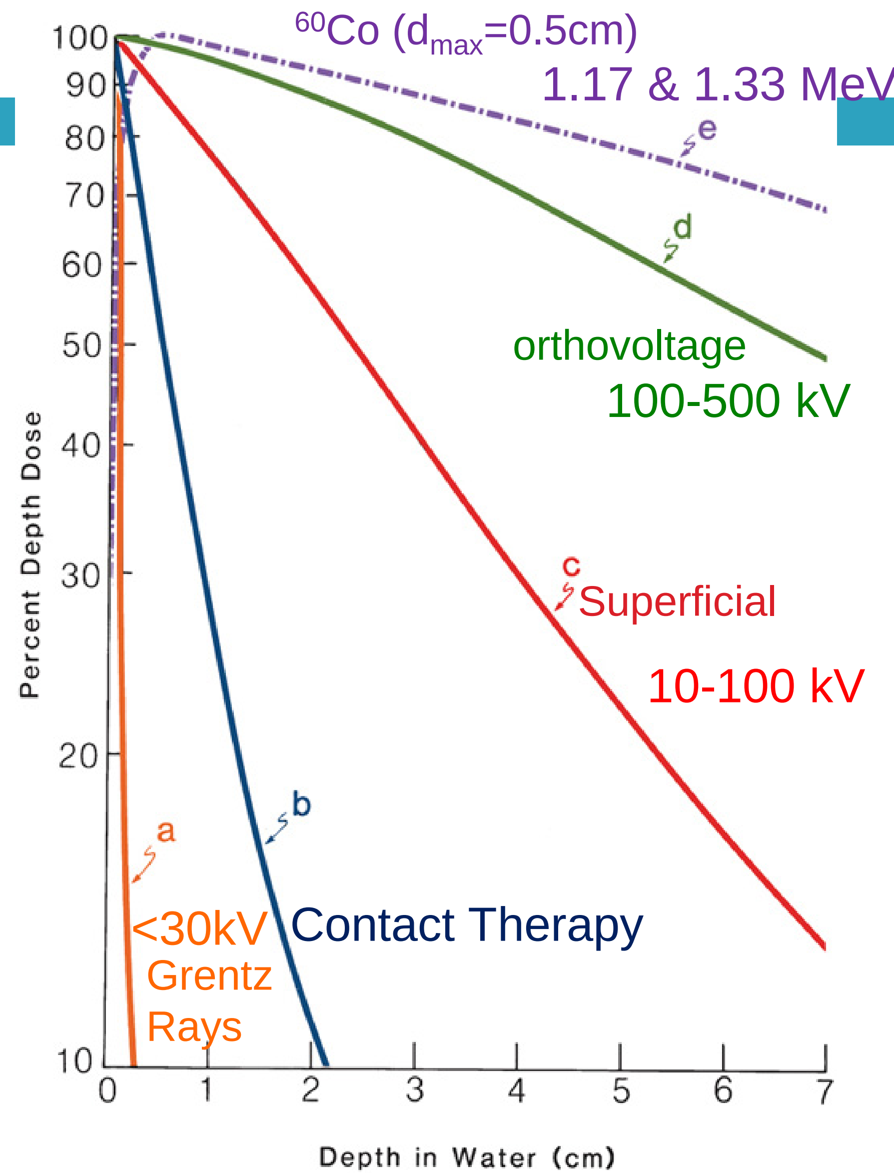
Depth-Dose Relationship for Different Energy Photons

$$\%DD = \left(\frac{D_d}{D_{d\max}} \right) \times 100$$

- For lower energies PDD is close to 100% at surface
- As increase energy 100% is at deeper depths

Increase Energy, Increase skin sparing

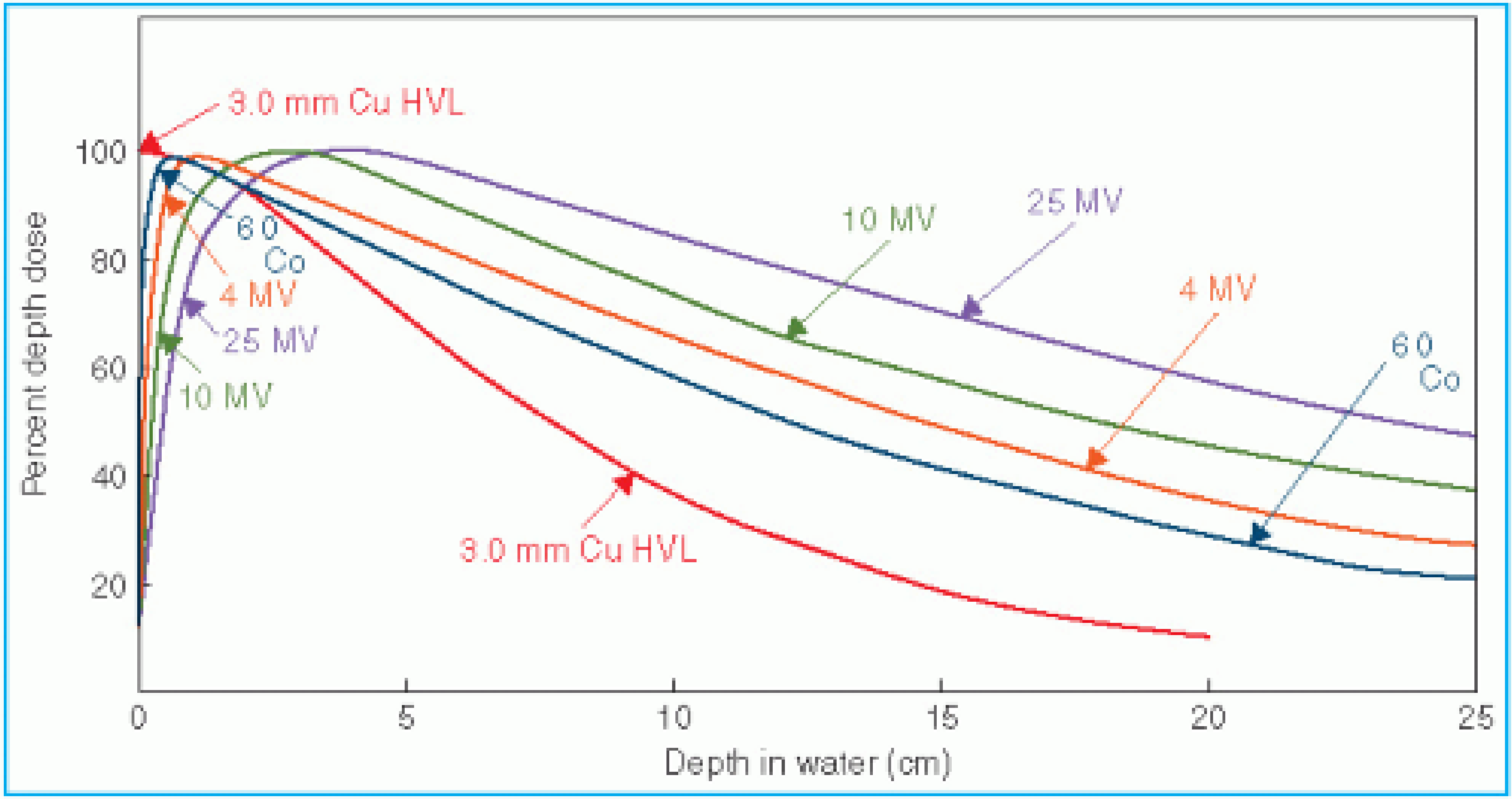
keV -> MeV energy: even more Skin Sparing



Depth-Dose Relationship for Different Energy Photons

keV to MEV: Increase Energy, Increase skin sparing, deeper penetration

$$\%DD = \left(\frac{D_d}{D_{d\,max}} \right) \times 100$$



Cutaway Diagram of Varian Linac

Khan, Figure 4.8C

Microwave Power = Photons!

- E=hv
- h=6.626*10^{-34} J*s
- v = frequency (1/s)
- Microwaves have very High Frequencies
  - High Energy

$$eV = 1.6*10^{-19}\,J$$

$$c = \lambda \nu$$

Resonance

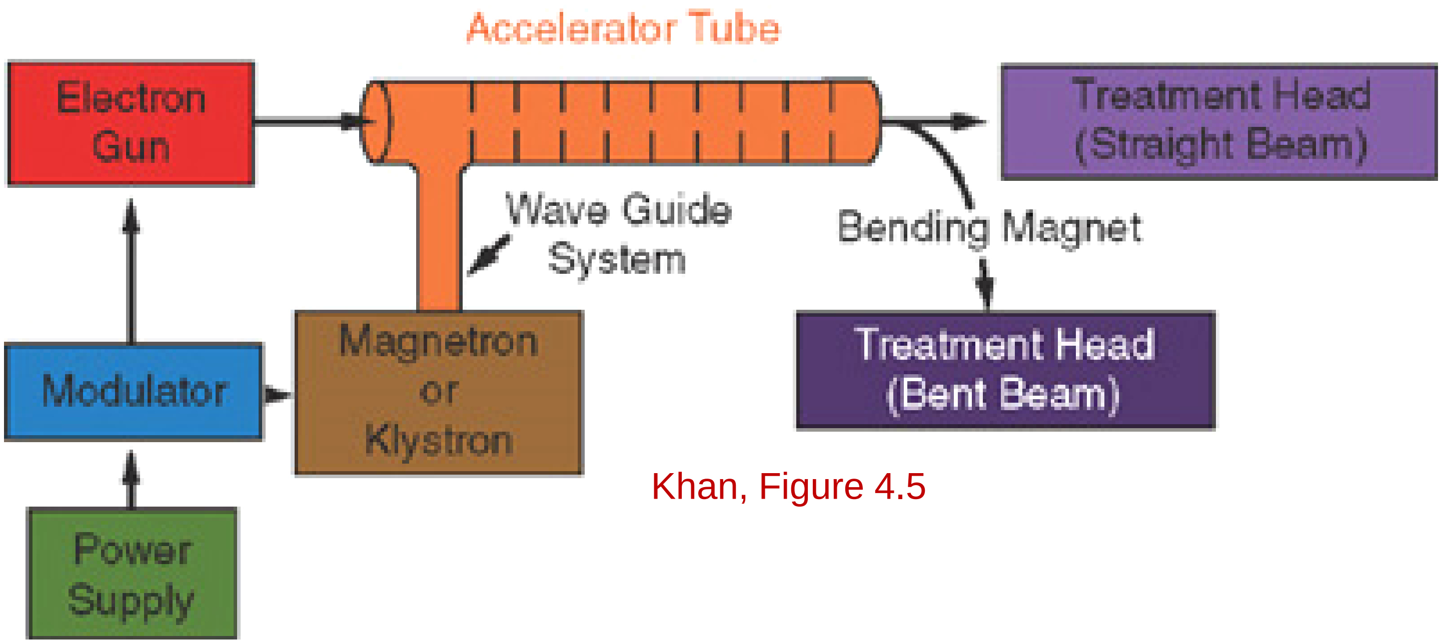
- Resonance causes an object to move back and forth or up and down. This motion is generally called oscillation.
- When the force application frequency matches the natural frequency of an object it will begin to resonate.
- The forcing function adds energy at just the right moment during the oscillation cycle so that the oscillation is reinforced.
  - This makes the oscillation's amplitude grow larger and larger.
  - It’s like pushing a swing… lots of little pushes at the right time…

Resonance

- In Radiation therapy microwave devices make extensive use of resonant microwave cavities:
  - Magnetrons
  - Klystrons
  - Accelerator Structure

- The resonance Phenomenon occurs at **3000MHz** (corresponding to a 10cm wavelength), which is determined by the dimensions of the cavity.
  - Cavities are formed of copper for high electrical and thermal conductivity.

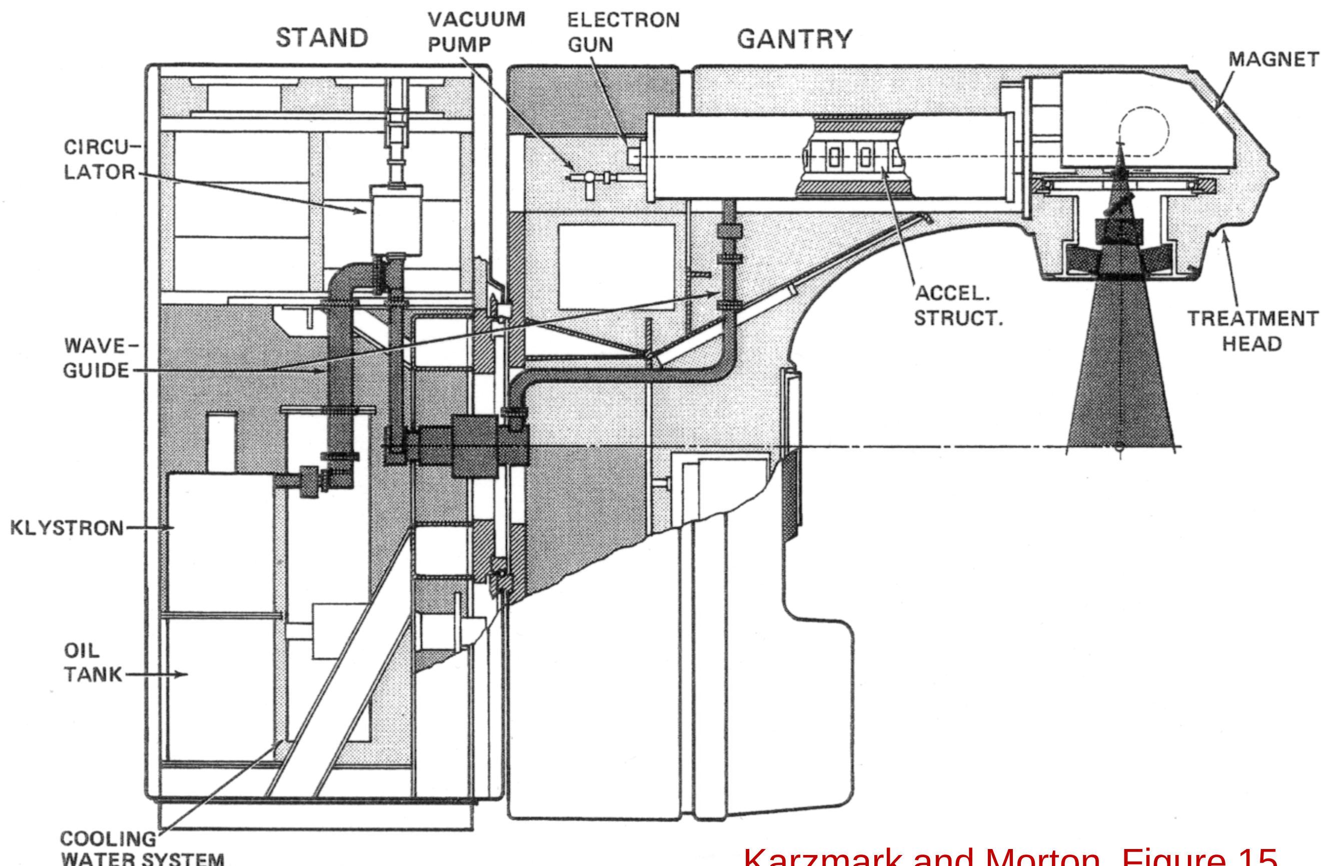
Typical Medical LINAC



Khan, Figure 4.5

Our Goal…
To understand all parts of this LINAC diagram!

LINAC Components: Varian "Clinac"

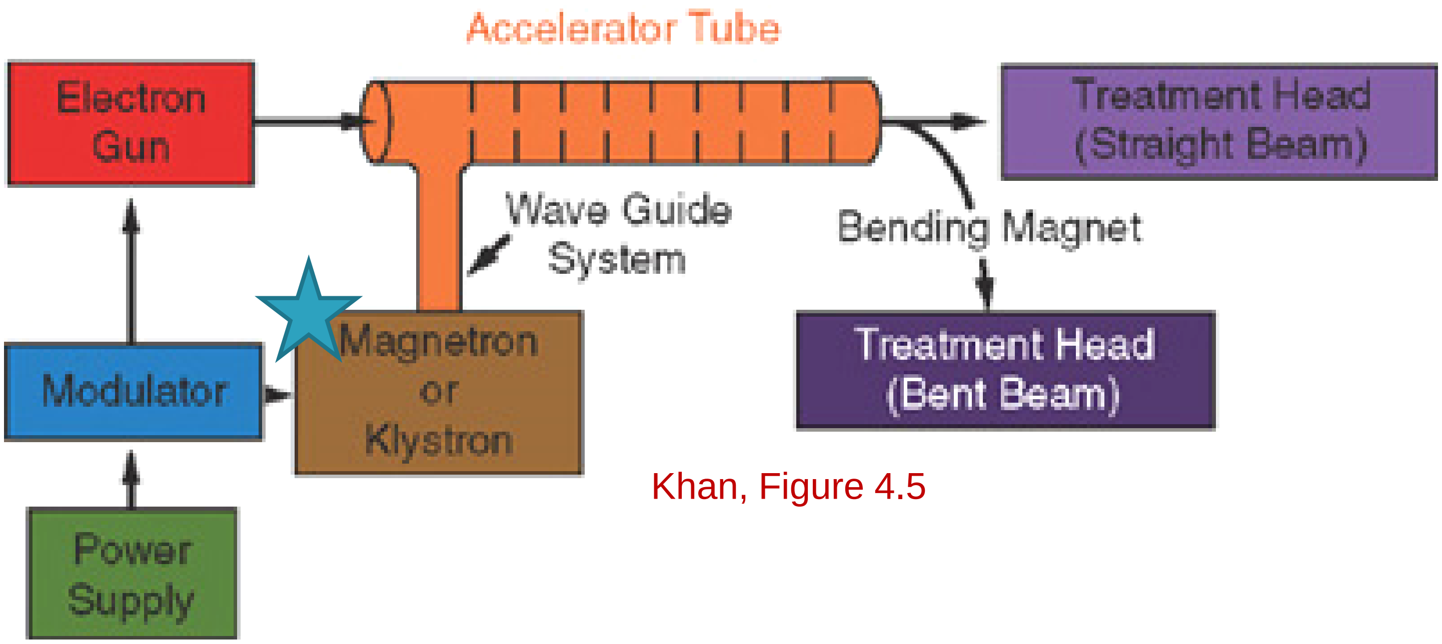


Karzmark and Morton, Figure 15

Basic LINAC Components

1. Modulator – Simultaneously provides high voltage DC pulses to the magnetron or klystron and e^- gun.
2. Magnetron/Klystron–provides high frequency microwaves.
3. Electron Gun – cathode that provides source of electrons injected into accelerator structure.
4. Wave Guide – Carries microwave power from magnetron or klystron through the accelerator structure.
5. Accelerator Structure – Accelerates e^-s from an electron gun using microwave power from magnetron or klystron.
6. Treatment Head– Directs, collimates, shapes, and monitors the treatment beam

Typical Medical LINAC

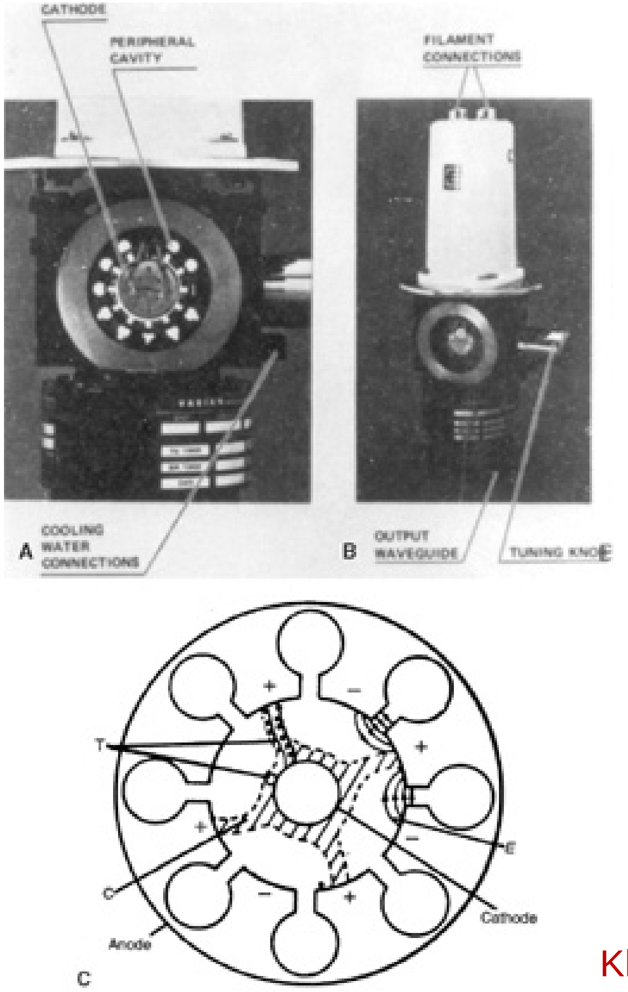


Khan, Figure 4.5

Magnetron/Klystron–provides high frequency microwaves.

The Magnetron

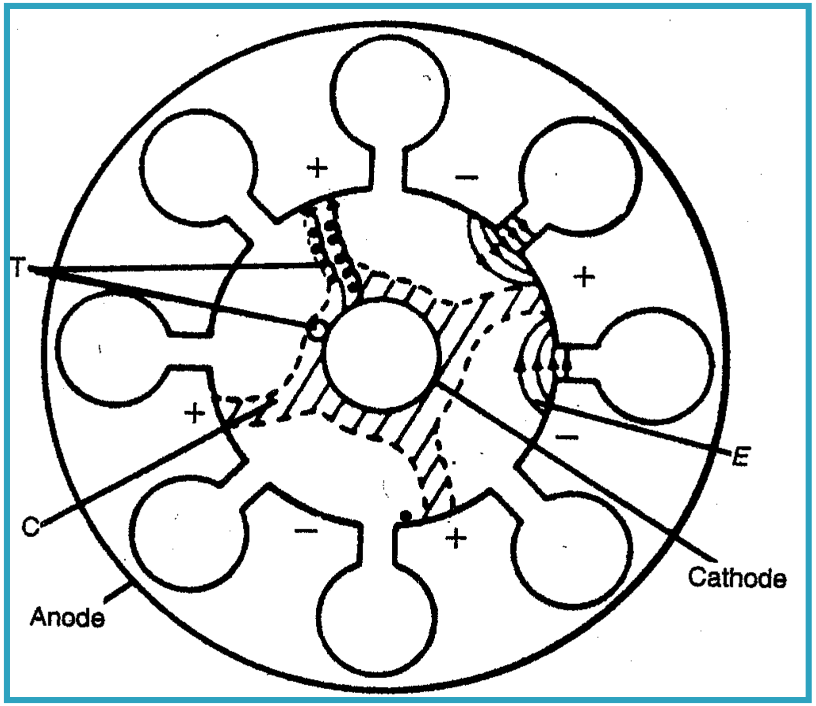
- Device that PRODUCES microwaves
- Cylindrical construction w/central cathode and outer anode w/resonant cavities



Khan, Figure 4.6

Magnetron
The Steps to Generate Microwaves

1. Cathode heated by inner filament.
   - e- released by thermionic emission.
2. Static magnetic field applied perpendicular to the plane of cavities cross-section.
3. Pulsed DC electric field applied between anode and cathode.
   - accelerating power



Khan, Figure 4.6c

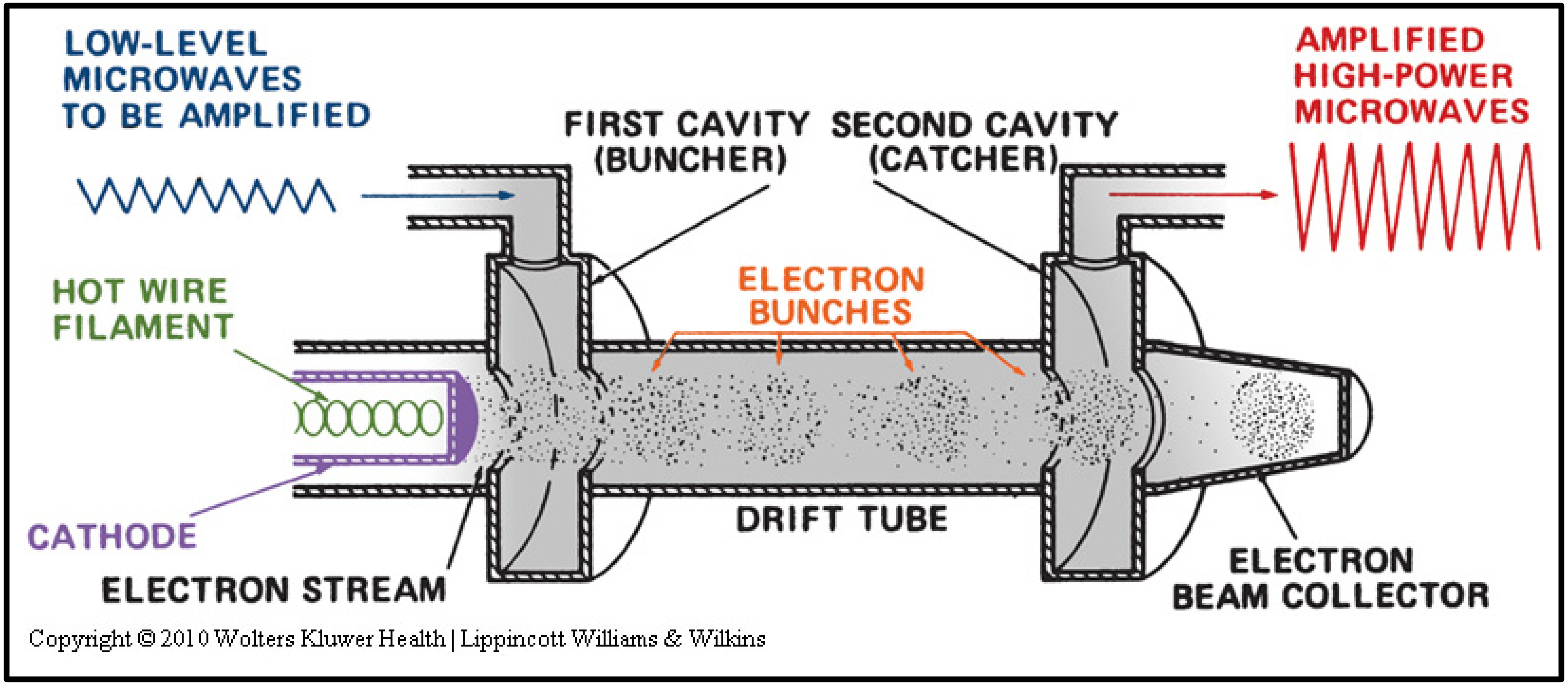
Magnetron

The Results

- The e-s released from cathode are accelerated toward the anode by the action of pulsed DC electric field.
  - e-s move in complex spirals toward the resonant cavities (due to influence of magnetic field), radiating energy in the form of microwaves.
- Microwaves are lead to accelerator structure via "waveguide".
  - Resonant Frequency → 3000MHz

Klystron

- Klystron = Microwave Amplifier driven by low power microwave oscillator.
  - Different from magnetron, does NOT generate microwaves.



Klystron

The steps of Microwave Amplification

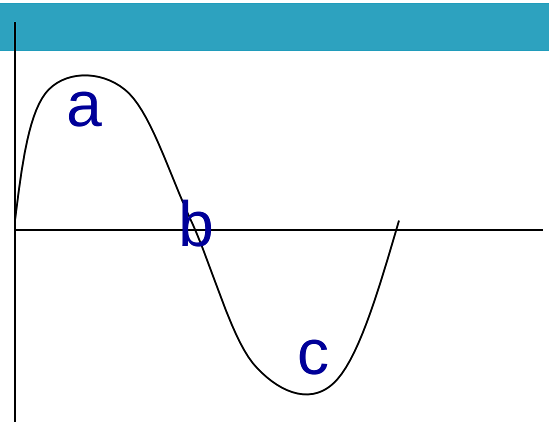
1. Cathode heated by hot wire → e-s released via thermionic emission.

2. Low level microwaves injected into buncher cavity.
   - Setup alternating electric field across the gap between left and right cavity walls

3. Velocity Modulation → Let's talk about this step in detail!!

Klystron-The steps of microwave amplification

Step 3. Velocity Modulation → More Details



- Electric Field Accelerates e^-s
+ Electric Field Decelerates e^-s

- Fast electrons that arrive in buncher cavity early, between points a and b, encounter a retarding Electric Field → Slowed
- Electrons that arrive at time b, when Electric Field=0 → velocity unaffected
- Slower e-s that arrive at buncher cavity later, between b and c encounter accelerating Electric Field → Accelerated

Net Effect

e- stream forms into bunches → groups of e^-s traveling at same velocity.

Klystron

The Rest of the Steps for Microwave Amplification

4. Drift tube - Distance along which electrons moving at different velocities merge into discrete bunches.

5. Catcher Cavity - As e-s leave drift tube and traverse catcher cavity gap, they generate a retarding electric field (like charges repel) at the ends of the cavity, initiating energy conversion process.
   - the e-s kinetic energy is converted to EM radiation…microwaves.

Klystron

The Rest of the Steps for Microwave Amplification

6. Microwaves are lead to accelerator structure via wave guide.

7. Collector: Residual beam energy that is not converted to microwave power is dissipated as heat in collector cavity (there are also some x-rays, thus encased in shielding structure).

Klystron

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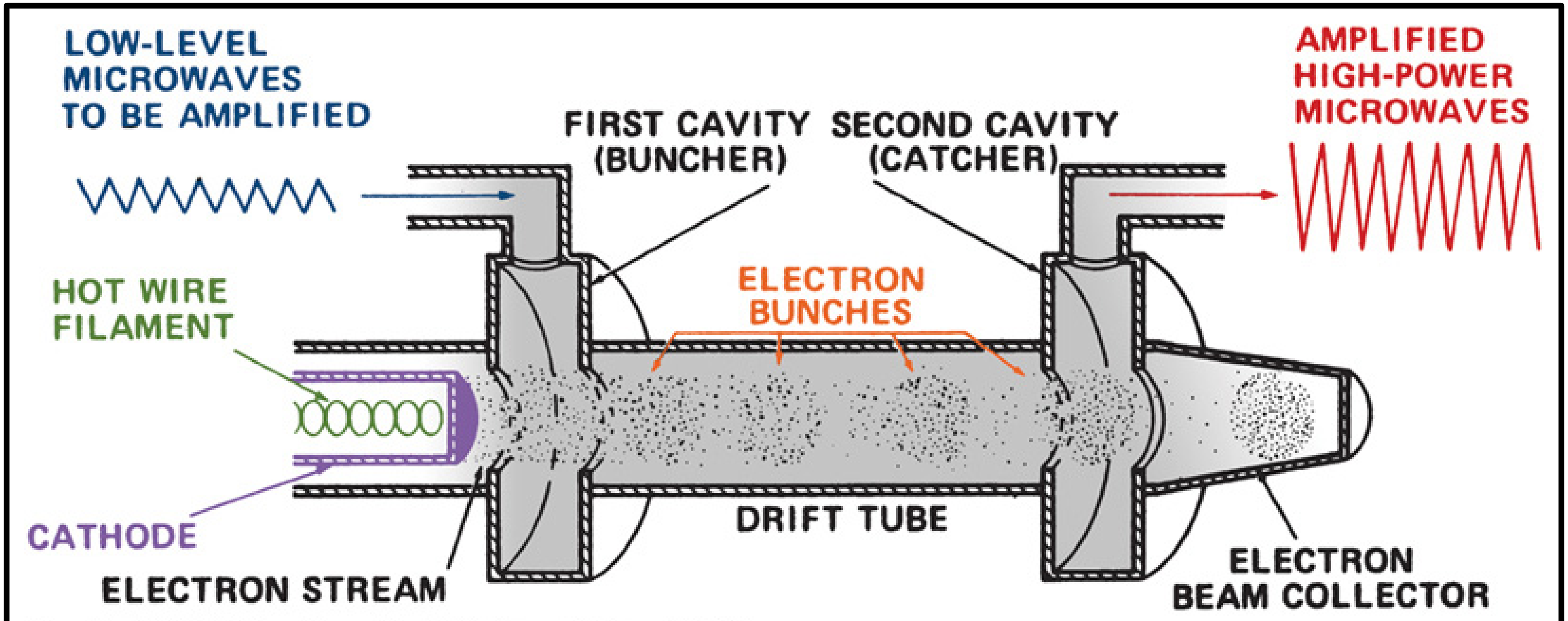


Magnetron verses Klystron

Magnetron

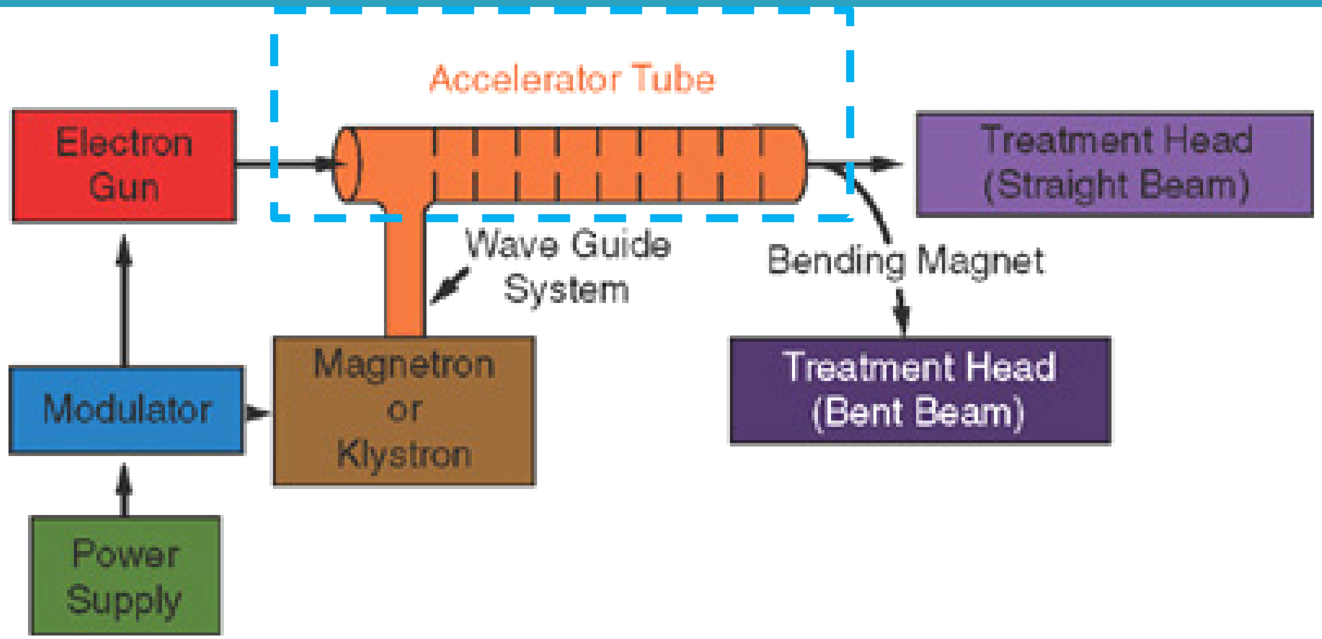
1. Used in Elekta
2. Circular Geometry
3. Typical Peak power 2MW (5MW in newer references)
4. Produces high frequency microwaves
5. Sends high frequency microwaves to accelerator tube via wave guide

Klystron

1. Used in Varian and Siemens
2. Linear Geometry
3. Higher Peak Power 5MW (7MW in newer references)
4. Amplifies Low frequency microwaves, resulting in high frequency microwaves
5. Sends high frequency microwaves to accelerator tube via wave guide

Same Result High Frequency microwaves to Accelerator Tube

Typical Medical LINAC



Let's discuss the accelerator tube in more detail.

Accelerator Tube

- Once we have microwave accelerating power (from either magnatron or klystron), we need a place to accelerate electrons:
- Accelerator Tube (Two Types)
  - Traveling Wave
  - Standing Wave

Don’t lose site of the goal:

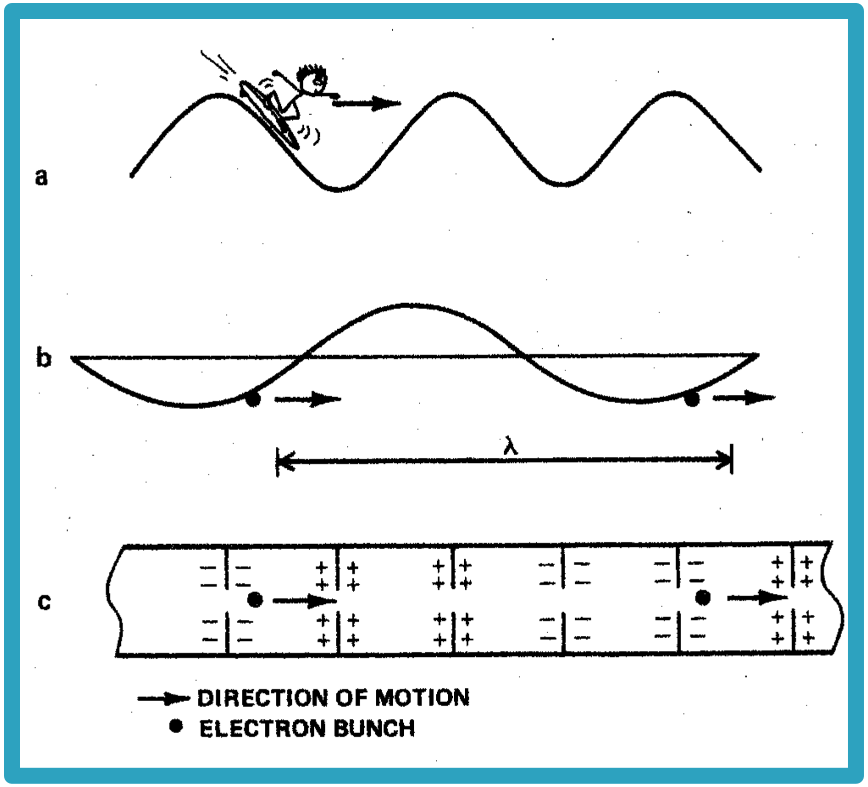
Accelerator Structure

Accelerates electrons from an electron gun using microwave power from magnetron or klystron

Traveling Wave-The Basics

- High frequency microwaves are transmitted down evacuated tube through accelerating cavities (≈ 3000 MHz).
- A pre-buncher is used to reduce the velocity of EM wave to correspond to speed of injected e^-s.
  - e^-s travel at crest of wave and undergo acceleration.
- EM waves are absorbed at end of accelerator to prevent backward reflected wave (which would interact with incoming waves).

Traveling Wave
Surfer Analogy



Karzmark and Morton, Figure 28

Traveling Wave Principle

a. A boy surfing on water wave, accelerates to the right.
b. e-s occupying a similar position on an advancing negative "E" field.
c. Associated charge distribution that pushes (- charge) and pulls (+ charge) the e- bunches along the cylinder

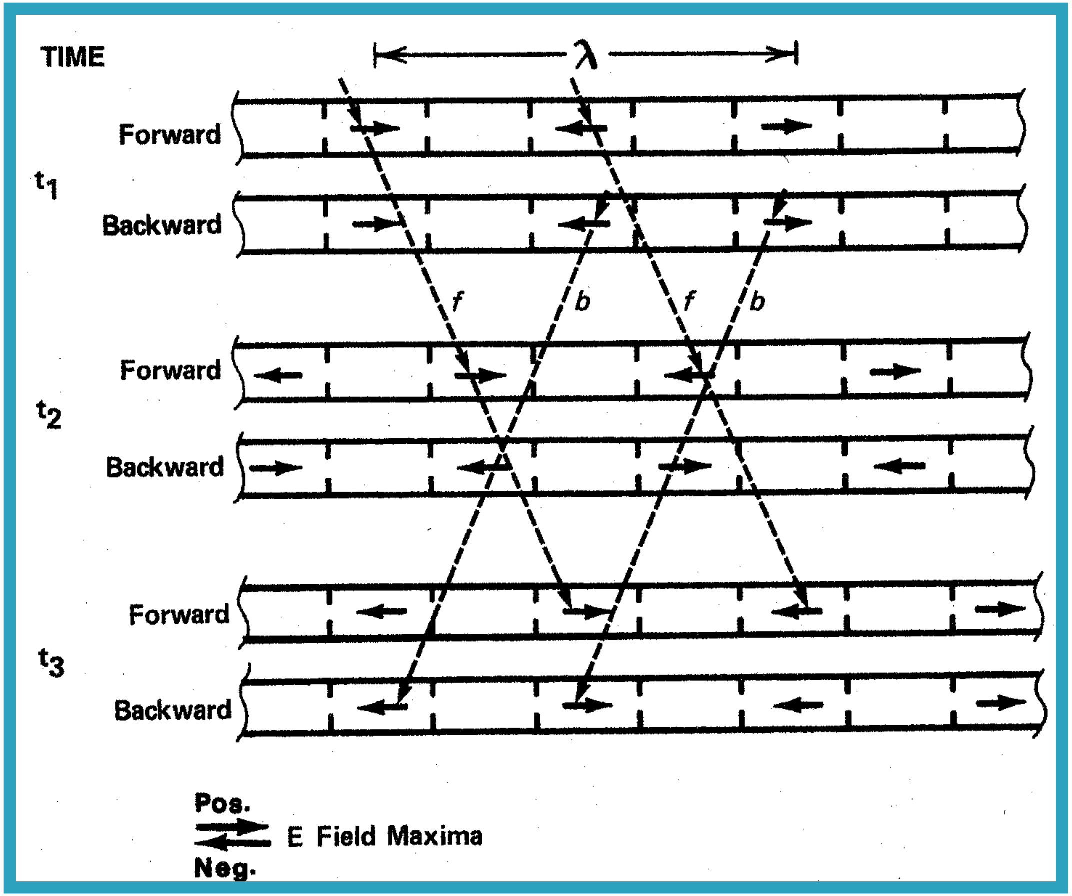
4 cavities per l

Standing Wave-The Basics

1. Microwave power is fed into the structure via input wave guide at proximal end (e- gun end).
2. Incident wave reflected backward.
3. Now we have 2 waves:
   - Incident wave
   - Reflected wave
4. The 2 waves are reflected back and forth from one end of the accelerator tube to the other many times.
5. The effective electric field is the sum of the forward and backward waves.
   - Magnitude of E fields is additive when the forward and backward waves are in same direction.
   - Magnitude of E field cancels out when forward and backward waves are in opposing directions.

Creating a Standing Wave

- Standing Wave Produced when 2 traveling waves of equal period and amplitude travel through waveguide in opposite directions!

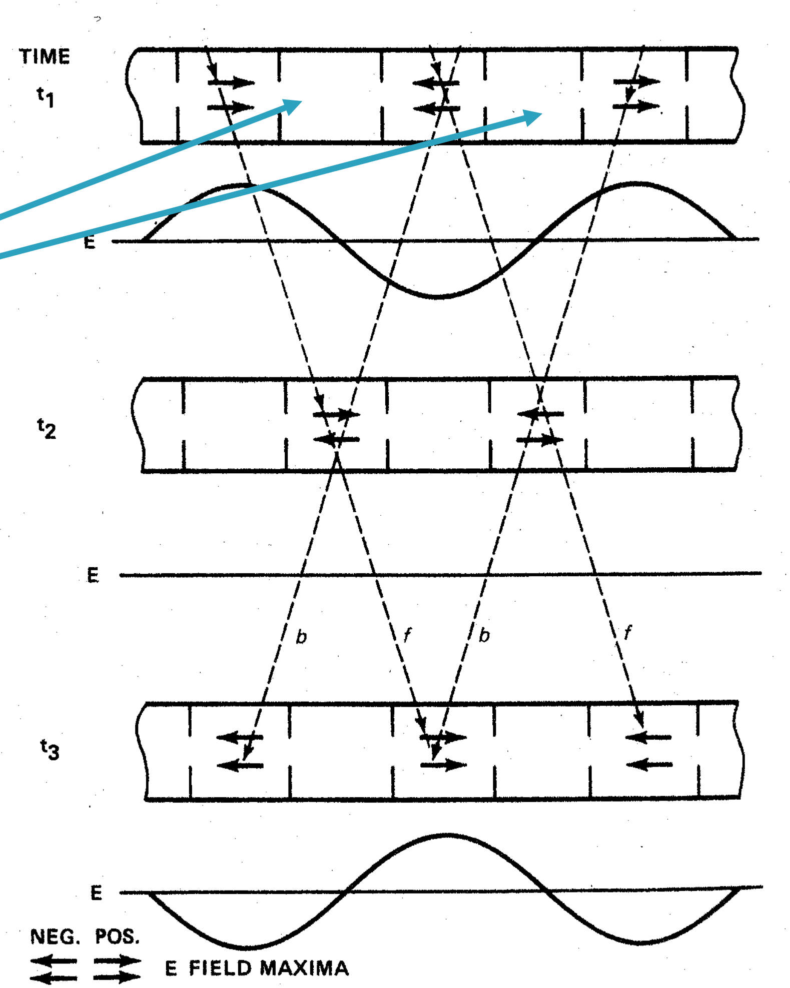


- In accelerator the forward and backward waves exist simultaneously, shown separately here for clarity.

Karzmark and Morton, Figure 29

Standing Wave

- Standing wave "E" field patterns in an accelerator structure for combined forward and backward waves @ three instances in time.
- Every other cavity "zero" electric field → essential in transporting microwave power, but do not contribute to e- acceleration.
  - Role=transfer and couple power bet cavities
  - Can be moved off axis to shorten length of cavity
- One in 4 cavities "negative".



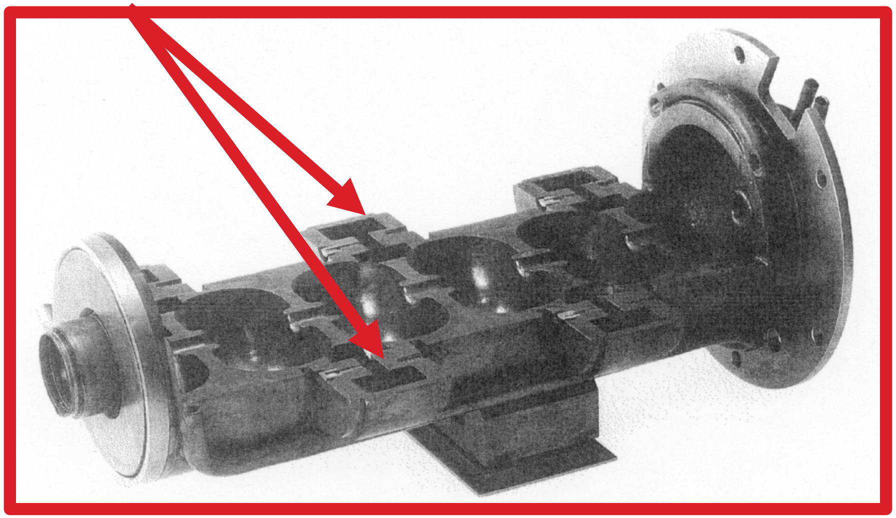
Karzmark and Morton, Figure 30

Bimodal (Side-Coupled) Accelerator

- Optimize cavities along the beam axis for acceleration
- Optimize off-axis cavities for microwave power transport

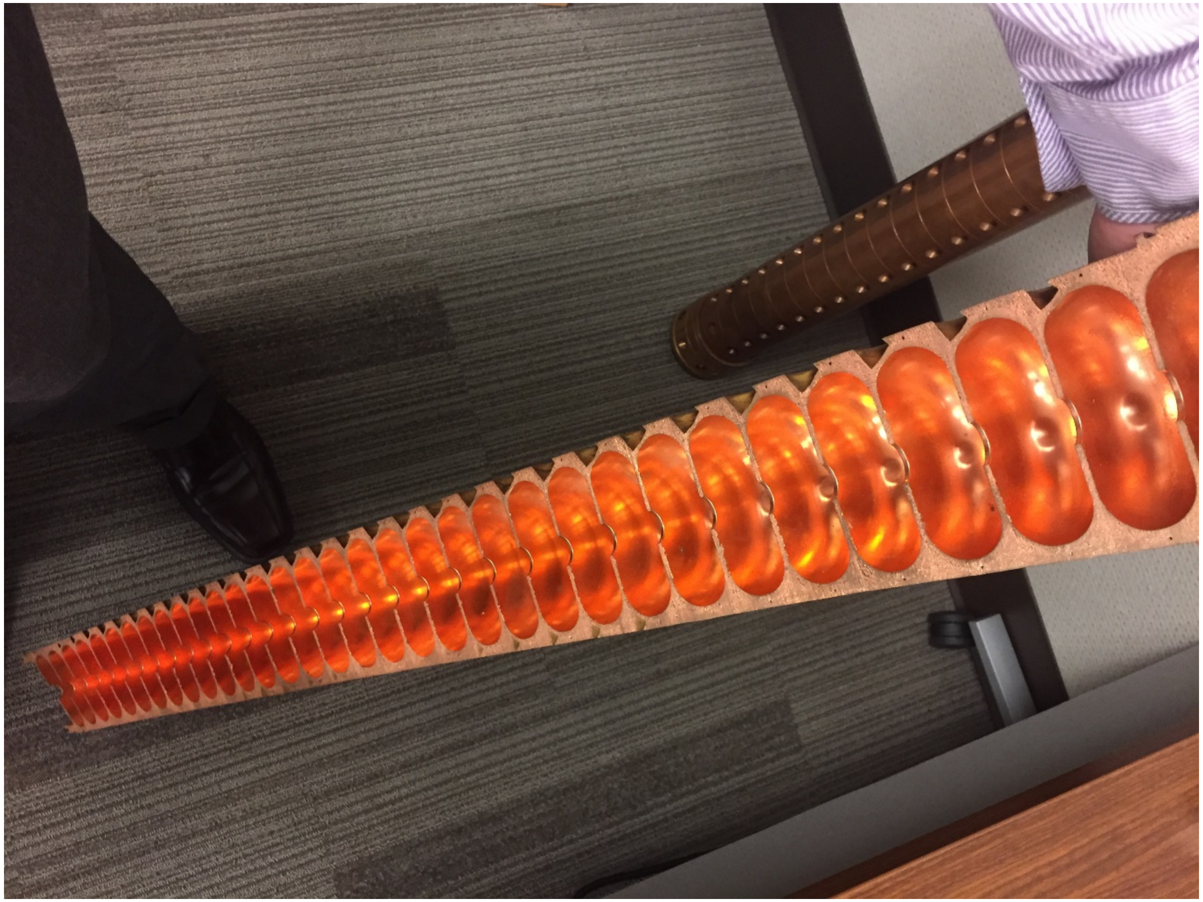
Result shorter Accelerator Structure, less space required in Rx room.

- Every other cavity “zero” electric field→essential in transporting microwave power, but do not contribute to e- acceleration
  - Role=transfer and couple power bet cavities
  - Can be moved off axis to shorten length of cavity



Accelerator Tube Example

- Elekta linac accelerator tube



Traveling Wave vs Standing Wave

Standing Wave

- More stable
- More expensive
- Shorter accelerator structure
  - Due to bimodal configuration
- Manufacturers
  - Varian
  - Siemens
- Usually used with Klystron

  Note: Single Energy (6X) standing wave accelerators often use Magnetrons

Traveling Wave

- Less stable
- Less expensive
- Longer accelerator structure
- Manufacturers
  - Elekta
- Usually used with Magnetron

What about LINACs with more than one beam energy?

Changing the beam energy will be different for traveling-wave and standing-wave accelerators.

Dual X-ray Energy Mode
A Summary

Karzmark, pg 26-28

Standing-wave	**Traveling Wave**
1. Change ratio of microwaves fed into first and second portions of cavity • Energy Switch: • High-power Microwave Circuit 2. Broad band buncher.	1. Beam Loading • Increasing injected beam current from gun and keeping magnetron or klystron power constant **Remember: Wave travels only in forward direction** • Amplitude of the "E" field in the second portion of accelerator structure can be changed without significant effect on first portion (capture and buncher)

One more step…..

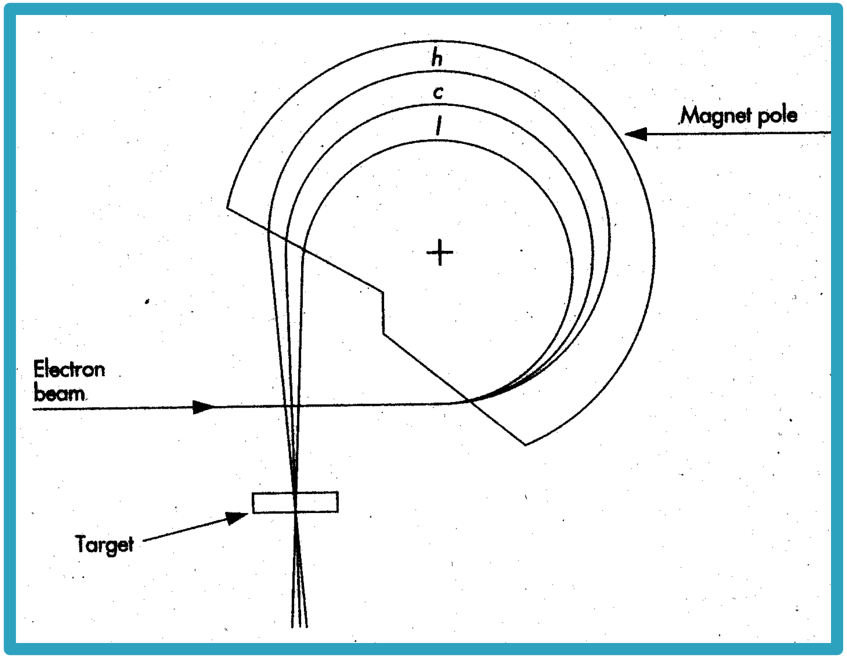
Where are we aiming the beam?

First things first
Where is the beam aimed

- Low energy, ≤ 6MV (standing wave) LINACs
  - Relatively short accelerator tube is vertically mounted, electrons proceed straight from accelerator tube to target.
- High energy ≥ 6 MV (standing Wave) LINACs
  - Accelerator tube too long to vertically mount, so horizontally mount the accelerator tube.
  - But now we have a problem → we have horizontal beam, BUT we want “vertical” beam!!

The solution = Bending Magnets

Bending Magnet – 270 degrees



- Deflects beam in 270º loop.
- Lower energy e^-s are deflected through smaller radius loop.
- Higher energy e^-s are deflected through larger radius loop.

All components brought back together at same position, angle, and beam cross section as when they left accelerator structure

Bending Magnet – Slalom Style

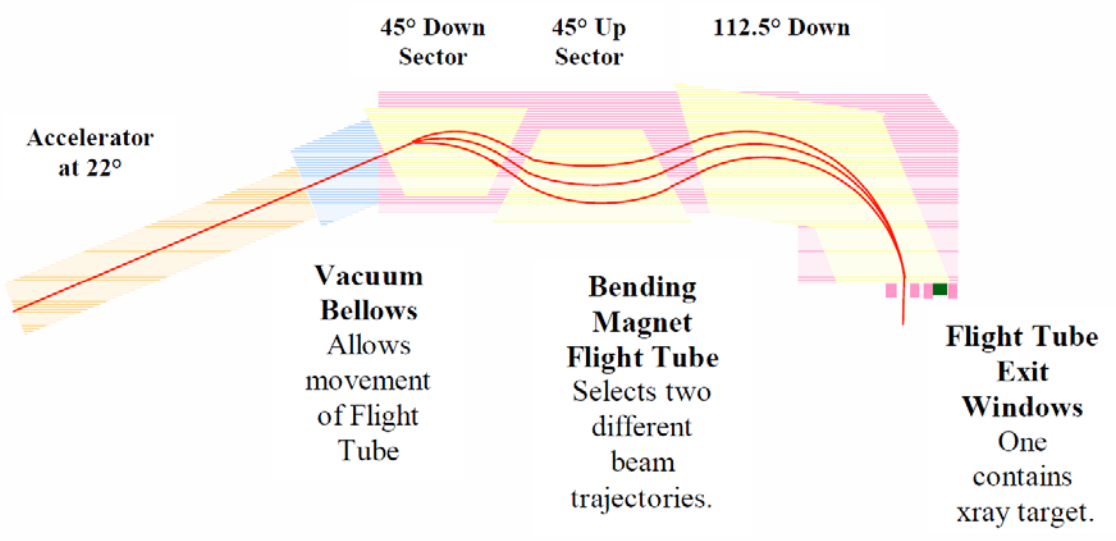


Figure 5: Simplified layout of 202.5° bending magnet system, flight tube, bellows, and dual ports (conceptual).

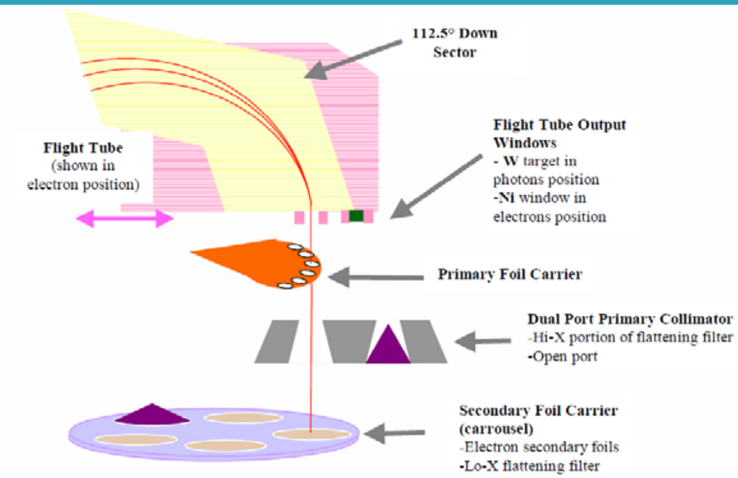


Figure 6: Elekta SL-25 beam modifiers/mode selection items in head of machine (conceptual).

Figure is from: Tim Waldron "The Theory and Operation of Computer-Controlled Medical linear Accelerators". 2002 AAPM Annual Meeting, Refresher Course. MO-A-517A-01 7/15/02

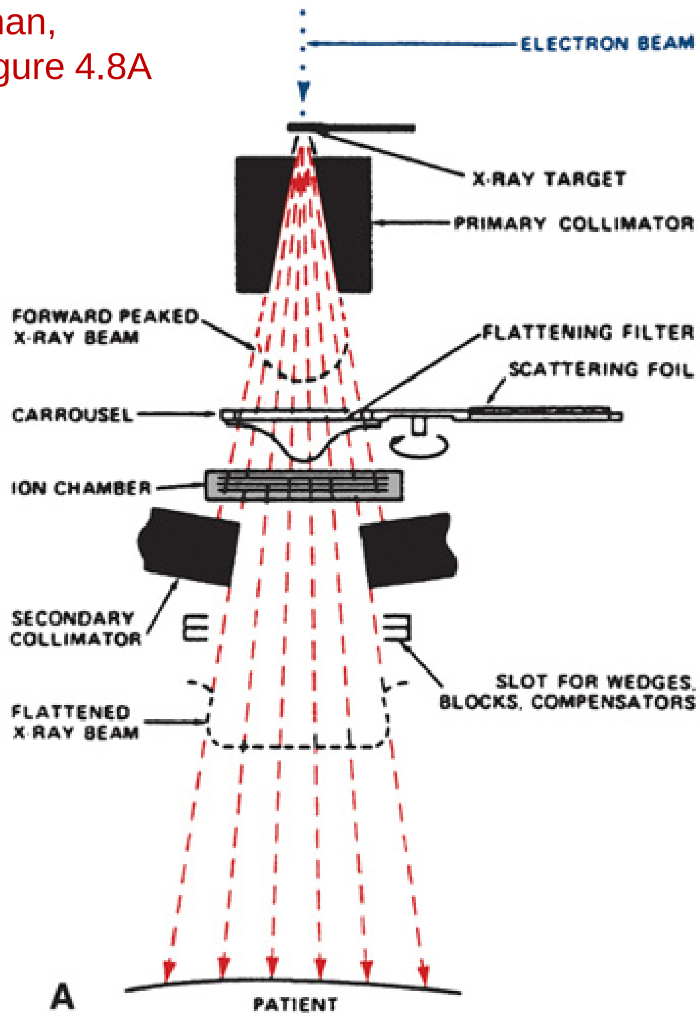
Now that we have that high energy e^- Beam, How do we make it useful for Rx?

What are we going to hit with it?

Do we want to treat with photons or electrons?

LINAC in X-Ray Mode

Khan,
Figure 4.8A

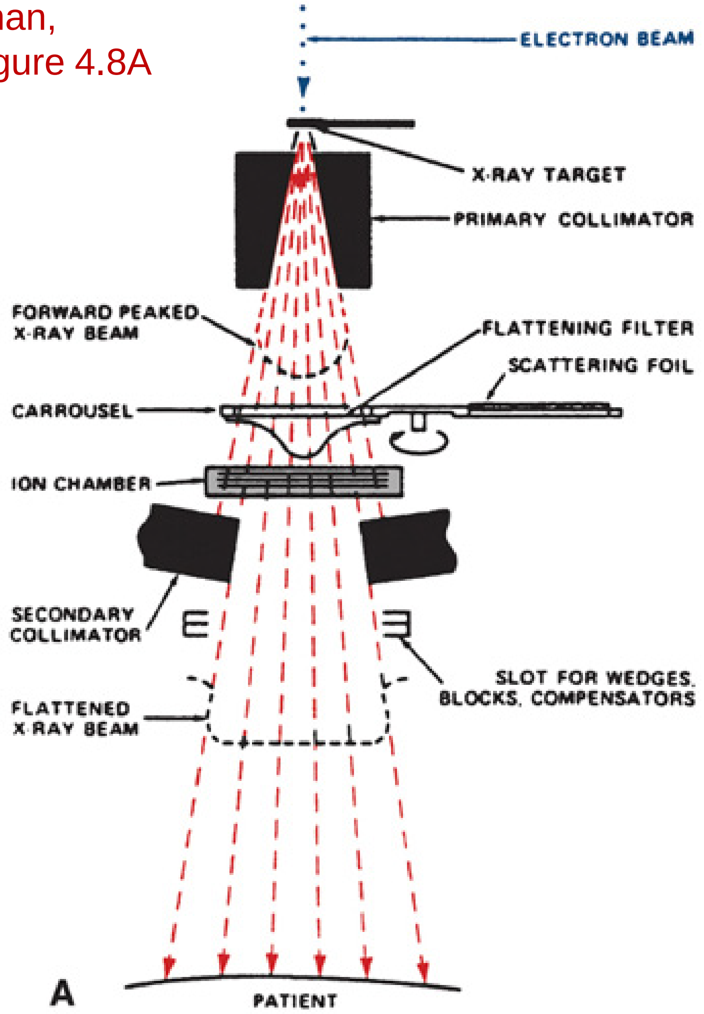


X-Ray Mode

- Target
- 1st collimation → fixed, non-variable
- Flattening Filter
- Monitor ionization chambers
- Field defining Light
- 2nd Collimator System
  - Multi Leaf collimators

LINAC in X-Ray Mode

Khan,
Figure 4.8A



X-Ray Mode

- Target

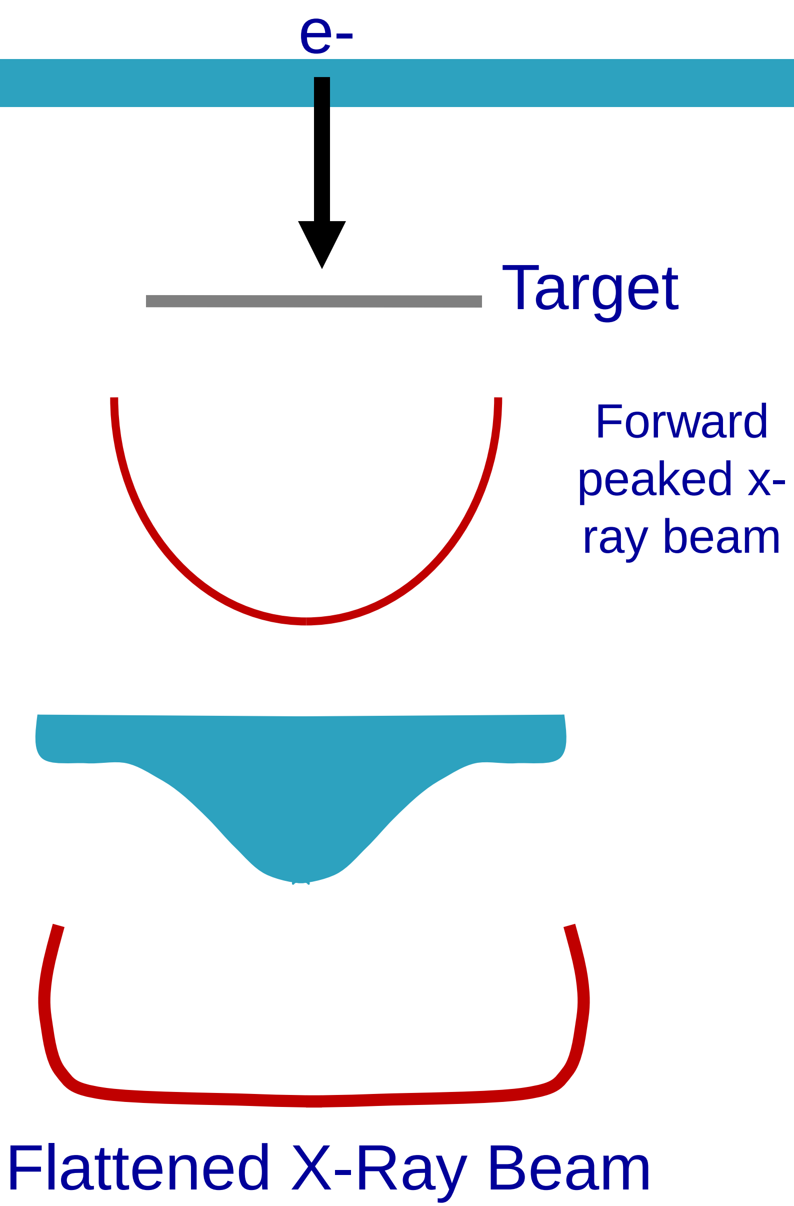
Flattening Filter

- High energy x-rays are forward peaked, max intensity located centrally with decreased intensity at periphery.

Flattening filter

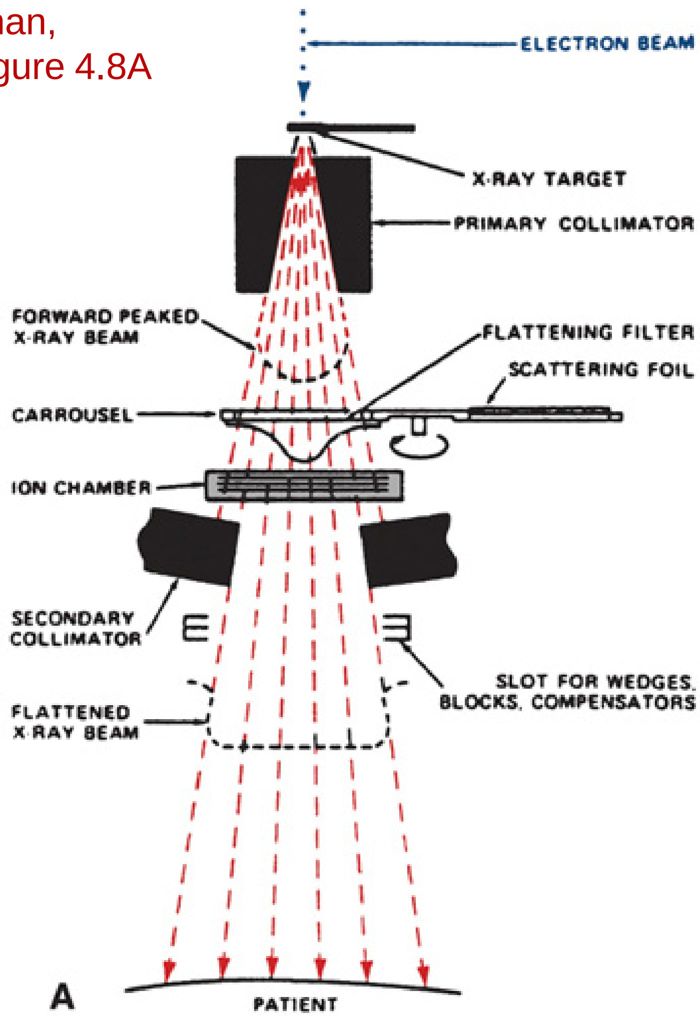
- thick at center
- thin at edges

Attenuates more photons from center less from edges: Flatter beam, covers more area



LINAC in X-Ray Mode

Khan,
Figure 4.8A



X-Ray Mode

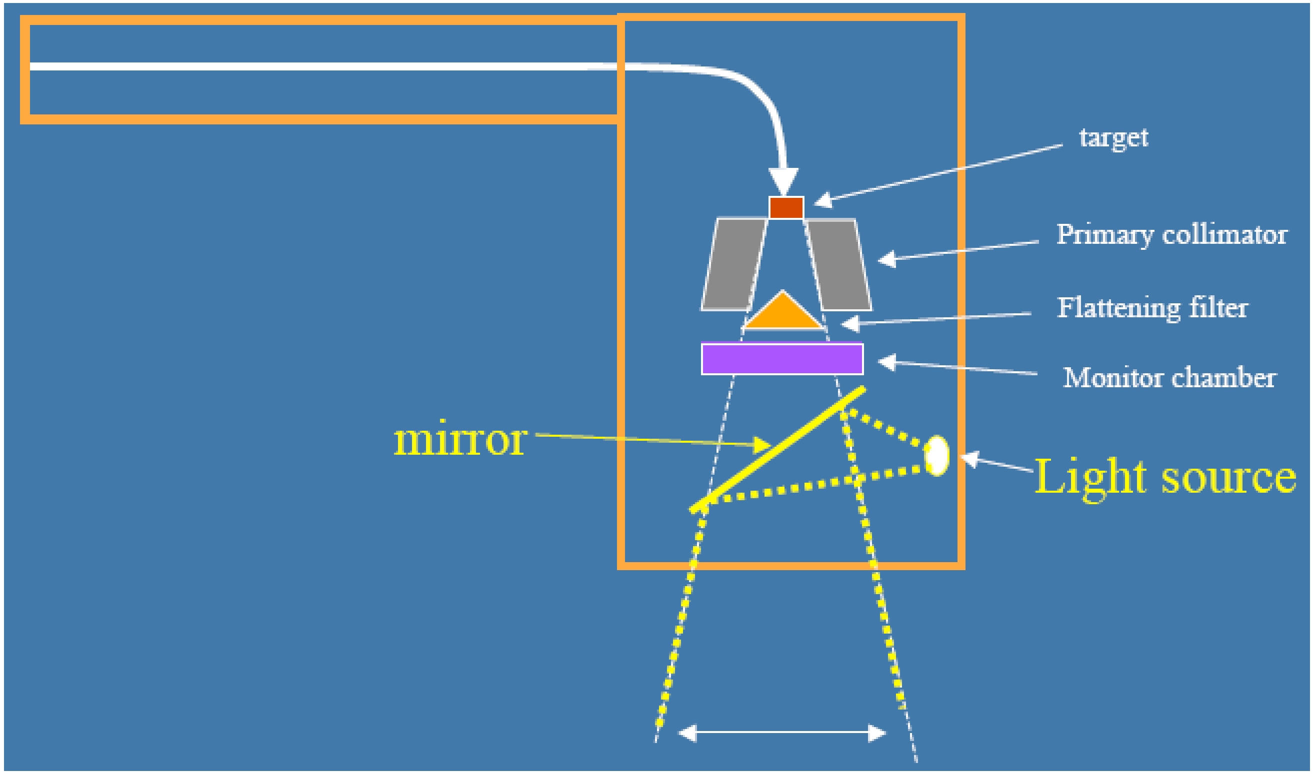
- Monitor ionization chambers

Monitor Ionization Chamber

- Dose Rate of accelerator beam may very unpredictable.
  - Therefore, cannot to rely on elapsed time to control dose delivered to patient.
- Radiation leaving target or scattering foil passes through monitor ionization chamber.
  - Radiation produces ionization current proportional to beam Intensity.
    - Current is converted to “monitor units” or MU
- Purpose of monitor ionization chamber:
  - Dose to patient controlled by programming accelerator to deliver prescribed # MU.
  - Monitor field symmetry.

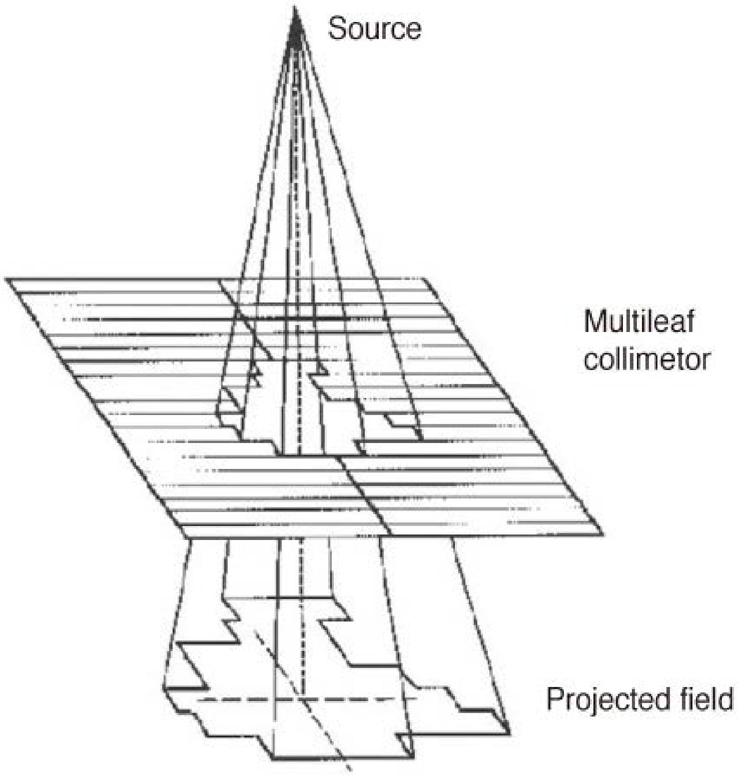
LINAC Light Field

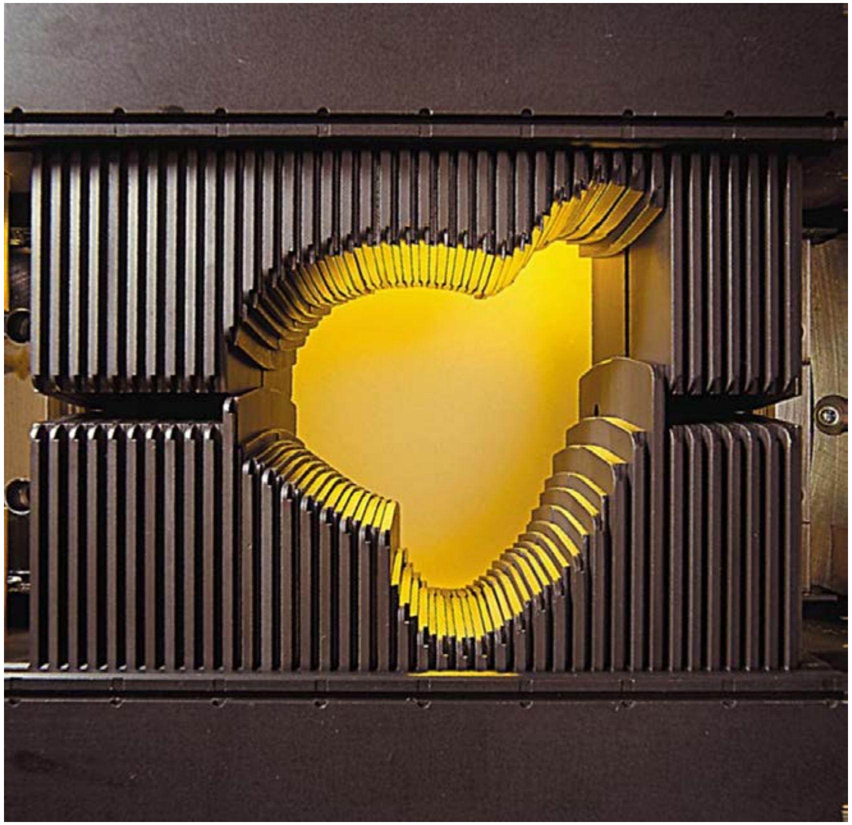
- To help see the “projected” field on our patients
- Mirror slides into place for visual verification, moves out of beam path when in use



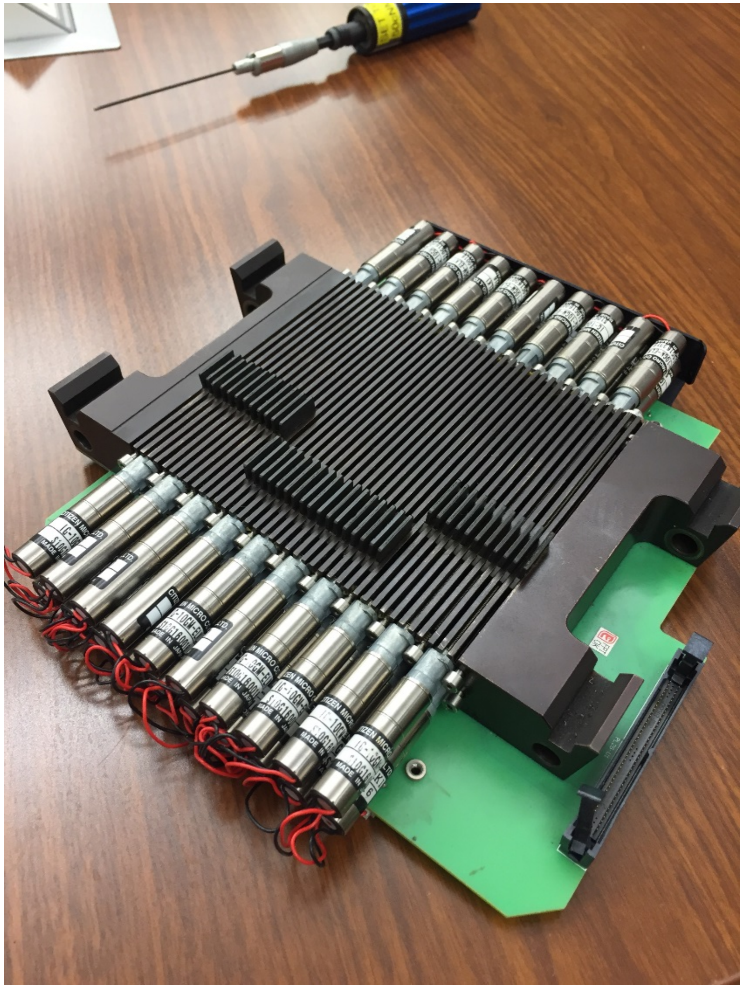
Multileaf collimators

- Devices using thick “leaves” of High Z material that help shape the exiting photon field laterally.

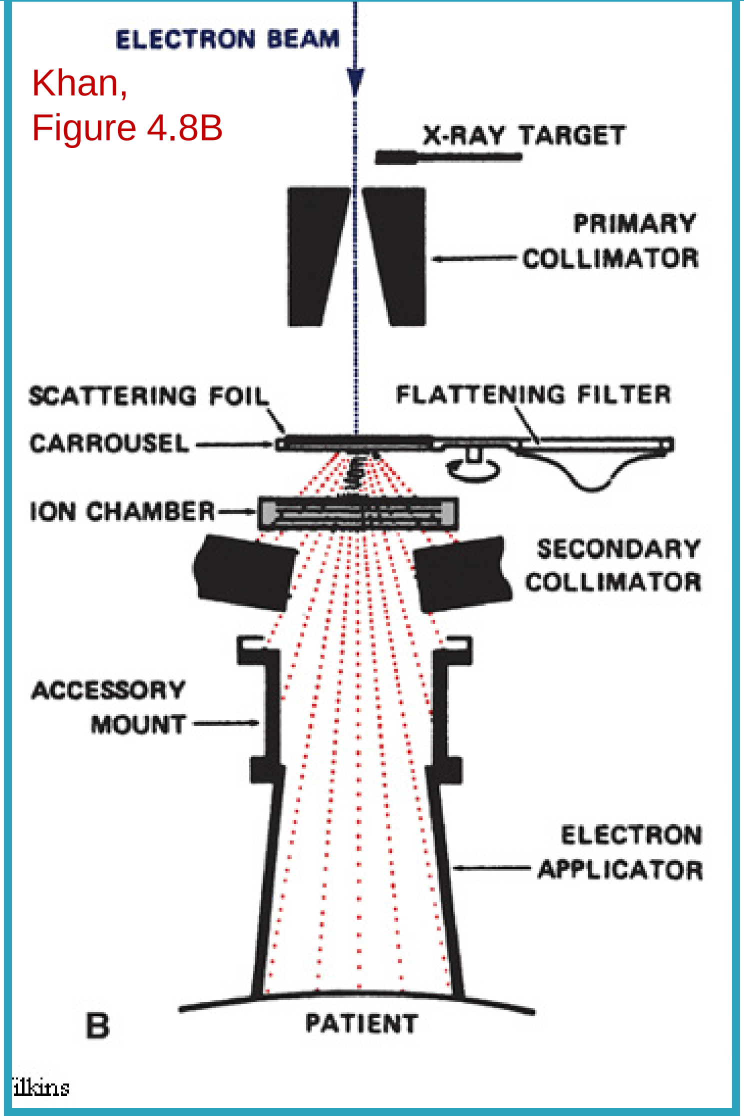




Multileaf collimators



LINAC in e- Mode



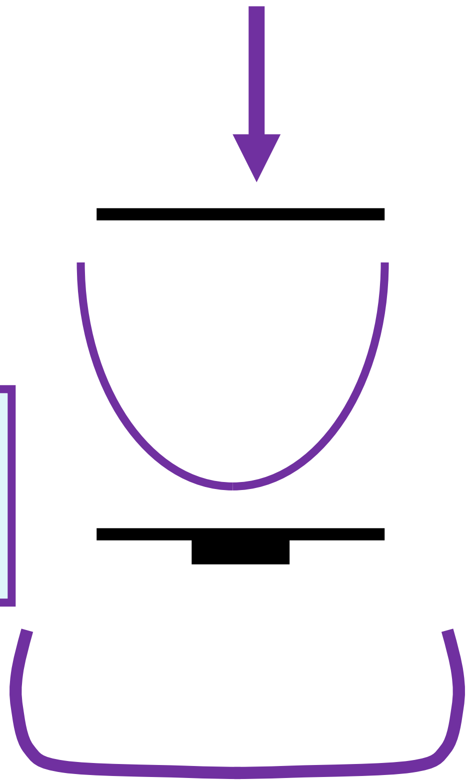
Electron Mode

- Scattering Foil
- Monitor ionization chambers
- Field defining Light
- Collimator System
  - 2nd e^- collimation = cone, downstream of photon collimators → placed close to skin to dec. e- scatter in air
  - 3rd e^- collimation = cutout downstream of cone → custom shape field to match Rx site
  - *Note: Beam flatness depends on design of cone or applicator.*

e^- mode NO TARGET!!

LINAC: e- Mode Scattering Foils

- Electron beam exits as narrow pencil beam with a small diameter.
  - Need to spread it out to be clinically useful.
- Effect of a single foil → Gaussian distribution
  - Unusable beam
  - Dual Foil System

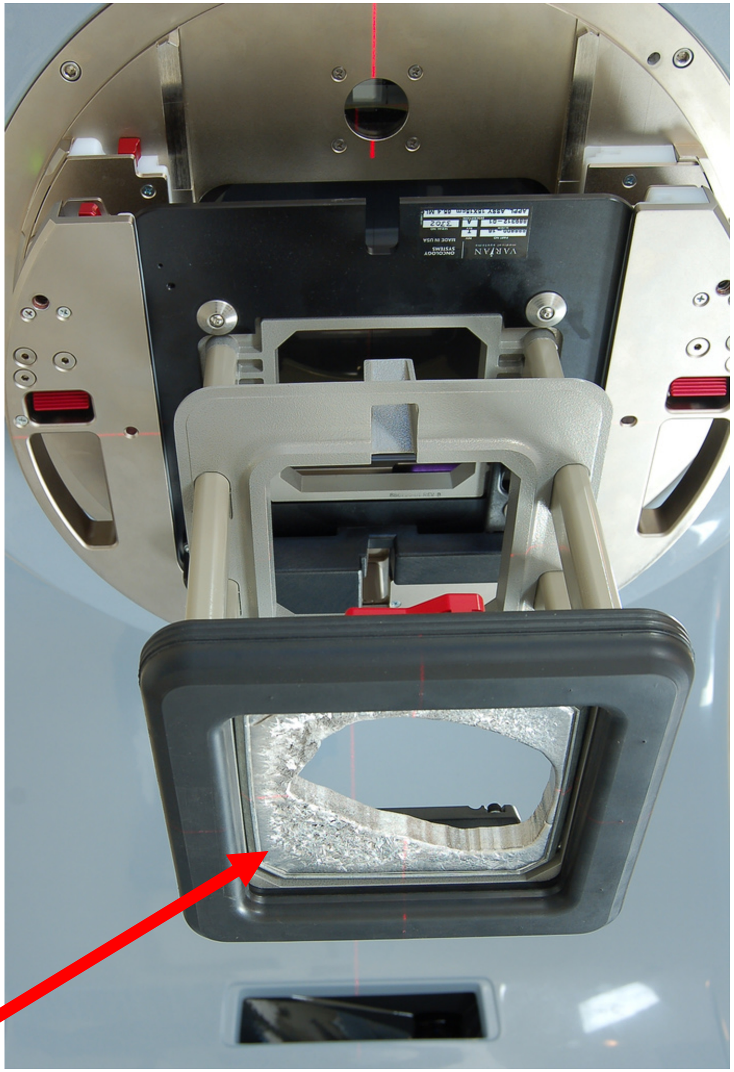


<u>2 High Z Foils separated by air gap</u>
2nd foil thicker at center to even distribution that results after beam passes through 1st foil

Note: thin foil, causes electrons to scatter i.e. spread out, thicker foils would result Brems. x-rays.

Electron Applicators or “Cones”

- Electrons are more likely to scatter in air and require additional, “closer” collimation
- Final field shaping of electron field by applicator and special insert
  - Lead insert custom shaped to specific treatment field size

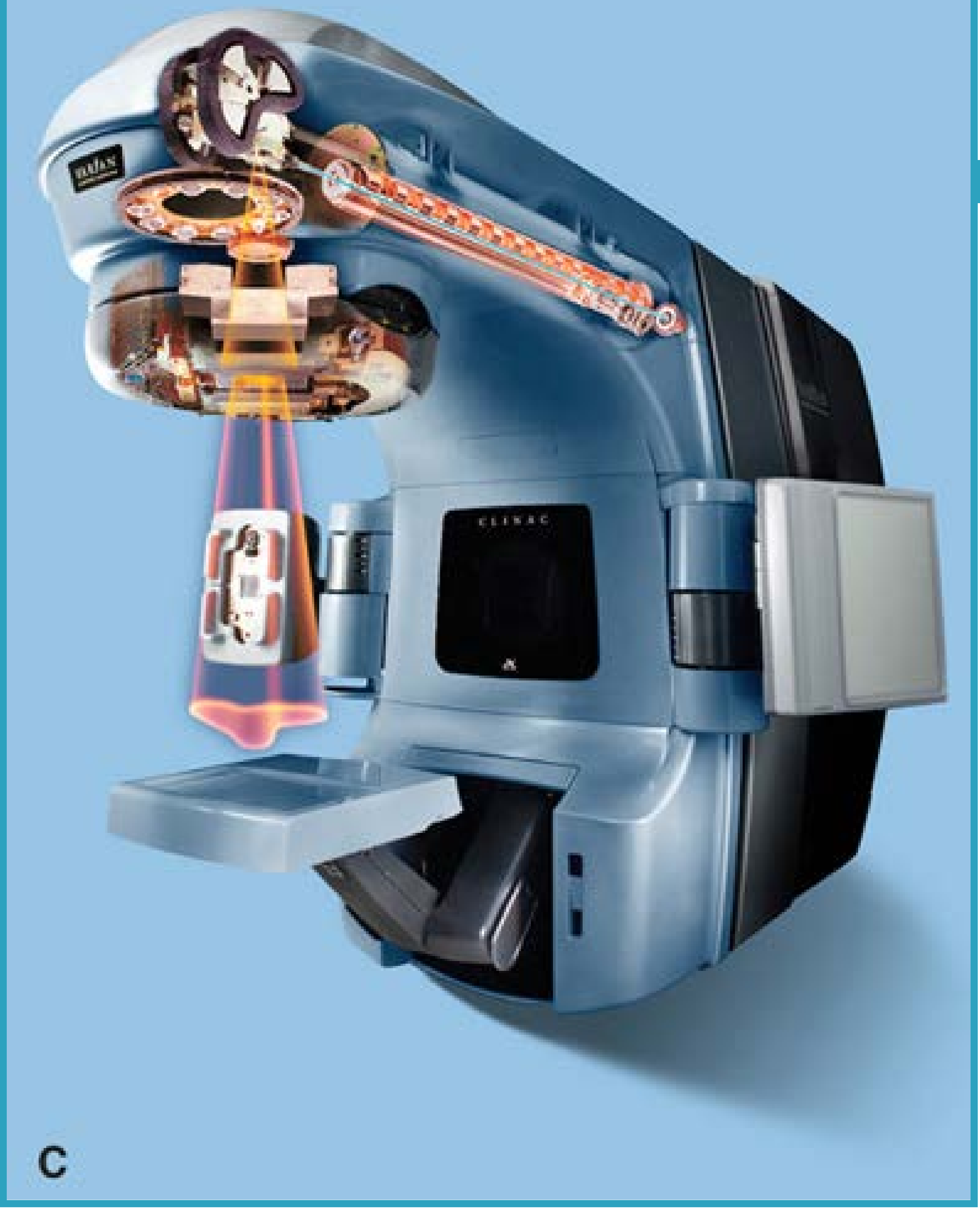


Cerrobend: 50% Bi, 27% Pb, 13% Sn , 10% Cd

Beam Current
Photon verses Electron Mode

- Beam current - number of electrons ejected from electron gun.
- Beam current is much higher in photon mode.
  - Recall: Bremsstrahlung production is inefficient.
  - Some of the photons are attenuated in flattening filter.

Cutaway Diagram of Varian Linac



Khan, Figure 4.8C

Practice Questions

If that was not too painful…

Question 1:

- The purpose of a scattering foil in the electron mode of LINAC is to :
  A. Absorb scattered electrons.
  B. Change x-ray beam into electrons.
  C. Shield the ion chambers.
  D. Absorb excess RF energy
  E. Broaden and flatten the beam.

Question 1:

- The purpose of a scattering foil in the electron mode of LINAC is to :
  A. Absorb scattered electrons.
  B. Change x-ray beam into electrons.
  C. Shield the ion chambers.
  D. Absorb excess RF energy
  E. Broaden and flatten the beam.

- Correct Answer: E. Changes narrow beam into a broader beam by forcing the electron path to spread due to collisions in the foil!

Question 2

- Which of the following does NOT occur when LINAC is changed from x-ray mode to electron mode ? (excluding units with scanned electron beams) .
  A. The target is removed.
  B. Scattering foil is placed in the beam.
  C. The monitor chamber is removed.
  D. An electron applicator is attached.
  E. The beam current decreases.
- Correct Answer: C. Monitor chamber NOT removed must monitor beam output for all modalities

Question 2

- Which of the following does NOT occur when LINAC is changed from x-ray mode to electron mode ? (excluding units with scanned electron beams) .
  A. The target is removed.
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  C. The monitor chamber is removed.
  D. An electron applicator is attached.
  E. The beam current decreases.

Question 3

- Klystrons and Magnetrons are:

  A. Devices used to bend beams of electrons.
  B. Located in treatment head of the LINAC.
  C. Beam focusing devices.
  D. Sources of microwave power.
  E. Part of the LINAC timer circuit.

- Correct Answer: D. Sources of microwave power (Magnetrons generate microwaves, klystrons amplify microwaves)

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  A. Devices used to bend beams of electrons.
  B. Located in treatment head of the LINAC.
  C. Beam focusing devices.
  D. Sources of microwave power.
  E. Part of the LINAC timer circuit.

-

Question 4

With regard to the production of electron beams by LINACs, which of the following is TRUE?

1. The Beam current is much higher in “electron mode” than in “photon mode”
2. Beam flatness depends on design of cone or applicator.
3. The bending magnet is rotated out of the beam when “electrons” are selected.
4. Thick scattering foils can reduce bremsstrahlung.
5. All of the above

Question 4

With regard to the production of electron beams by LINACs, which of the following is TRUE?

1. The Beam current is much higher in “electron mode” than in “photon mode”→ **No** photon production inefficient, need more current
2. Beam flatness depends on design of cone or applicator. → **TRUE**
3. The bending magnet is rotated out of the beam when “electrons” are selected.→ No required to point electrons down toward isocenter.
4. Thick scattering foils can reduce bremsstrahlung.→ **No** thicker foils result in more interactions and produce more x-rays!
5. All of the above

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