C5-Equipment

Principles and properties of radiation generating equipment; radiation sources; radiation receptors; radiation therapy equipment; diagnostic radiological equipment; nuclear medicine equipment; ultrasound equipment; nuclear magnetic resonance equipment; and related subjects.

- **C5-A (MLC)**

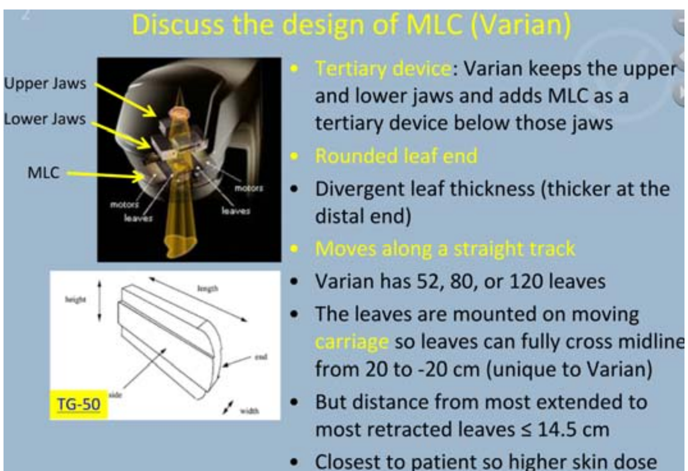
- If shown an image of a linac with light going through an MLC shape. What makes the shape? (MLC)
- MLC design: explain the design available from the 3 vendors and the different kind of leakage, sizes, focus options, why Varian has rounded leaves?

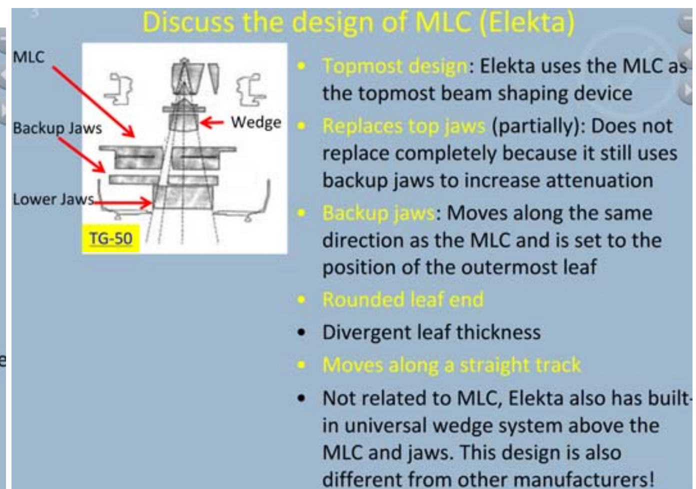
MLC adv:

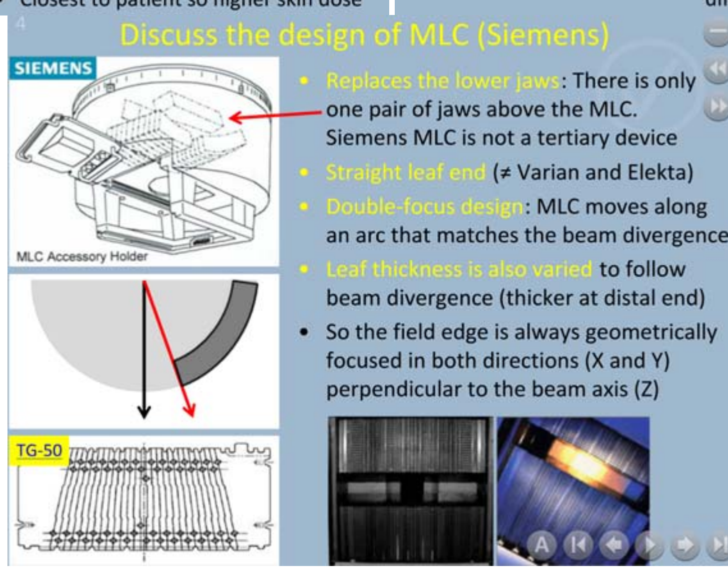
(1). Replace conventional cerrobend block, reduce labor work

(2). enables conformal therapy by adjusting field shape from one beam angle to another following the projection of the target shape, and

(3). enable intensity modulation.



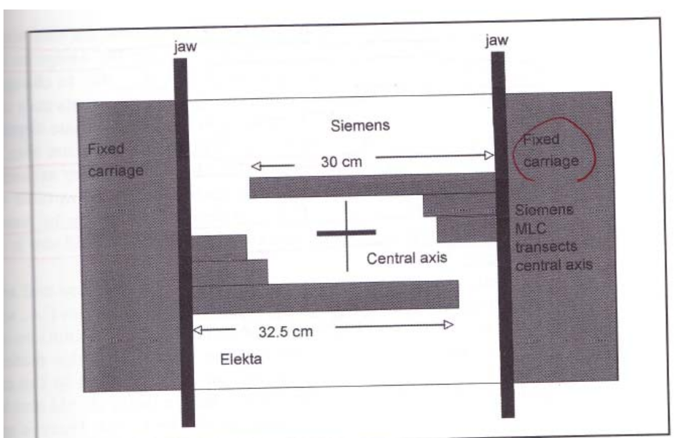




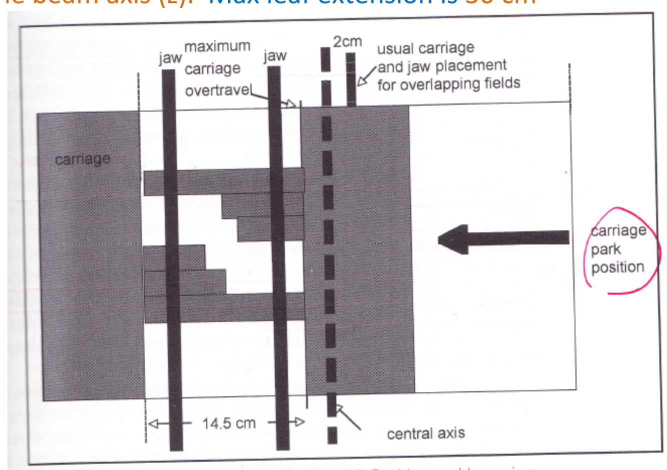
- Varian keeps the upper and lower jaws and adds MLC as a tertiary device below those jaws, so the higher skin dose. Divergent leaf thickness (thicker at the distal end), moves along a straight track (52, 80 and 120 leaves), and rounded leaf end. The leaves are mounted on moving carriage so leaves can fully cross midline from 20 to -20 cm (unique to Varian, traveling 40 cm of the field). But distance from most extended to most retracted leaves < 14.5cm. Single focus

- Elekta uses the MLC as the topmost beam shaping device, which replaces top jaws partially but does not replace completely because it still uses backup jaws to increase attenuation. Backup jaws move along the same direction as the MLC and is set to the position of the outermost leaf. It has rounded leaf end and divergent leaf thickness, moves along a straight track. Elekta also has built-in universal wedge system above the MLC and jaws. This decision is also different from other manufactures. Max leaf extension is 32.5 cm. Single focus

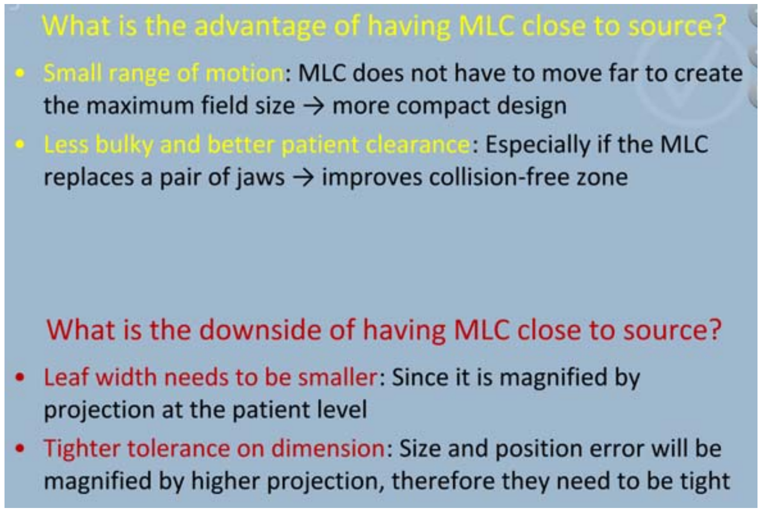
- What is a double focused MLC? Explain the functioning of it? And advantage?
  - Siemens MLC replaces the lower jaws, and there is only one pair of jaws above the MLC. It is not a tertiary device, and it has straight leaf end. It has double focused design: MLC moves along an arc that matches the beam divergence. Leaf thickness is also varied to follow beam divergence (thicker at distal end). So the field edge is always geometrically focused in both directions (x and y) perpendicular to the beam axis (z). Max leaf extension is 30 cm



(a): Leaf span and over-center travel of Siemens and Elekta MLC with fixed carriage.

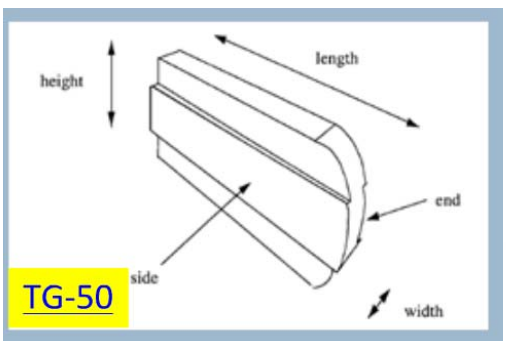


(b): Leaf span and over-center travel of Varian MLC with movable carriage.



(such as Elekta)

- Discuss the double vs single focused MLC's.



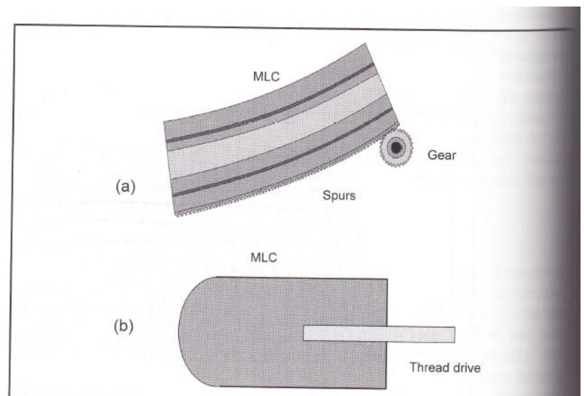
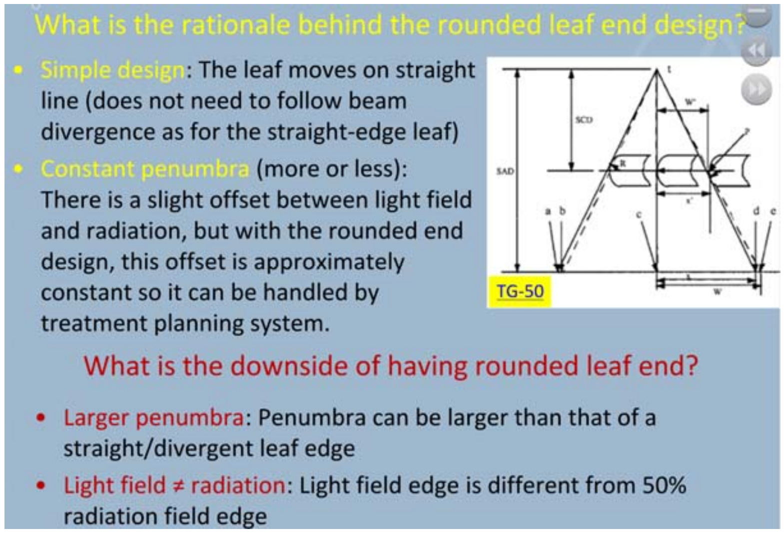


Figure 4.33: Schematic showing different MLC designs: (a) dual-focus MLC with spur gear; focus MLC with rounded leaf end.

What is single and double focusing design?

(MetCalf p 296) Penumbra width is minimized by presenting the beam with a focused diverging leaf side construction. This is achieved by designing the MLC leaves with a divergence focused on the x-ray source. Because the leaf side diverges, this is known as single-focus MLC.

The leaf can also be focused in the direction of lead motion (end). This is achieved by maintaining the leaf end parallel to the radiation beam, independent of the leaf position across the field. Siemens MLC (straight edge leaf) achieves double focusing by combining a leaf side divergence and an arced path of motion for each lead in direction of leaf travel.

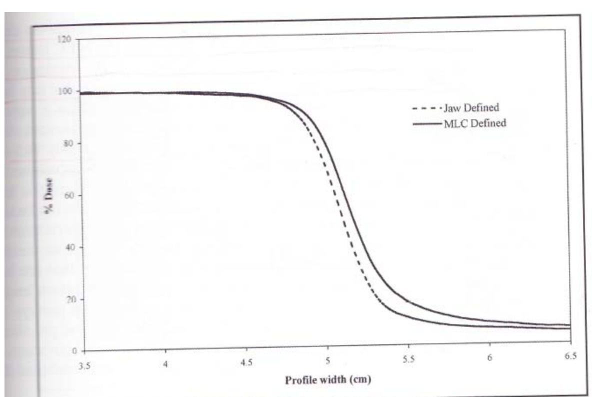


Why rounded leaf design?

ADV: Simple design: The leaf moves on straight line (does not need to follow beam divergence as for the straight-edge leaf).

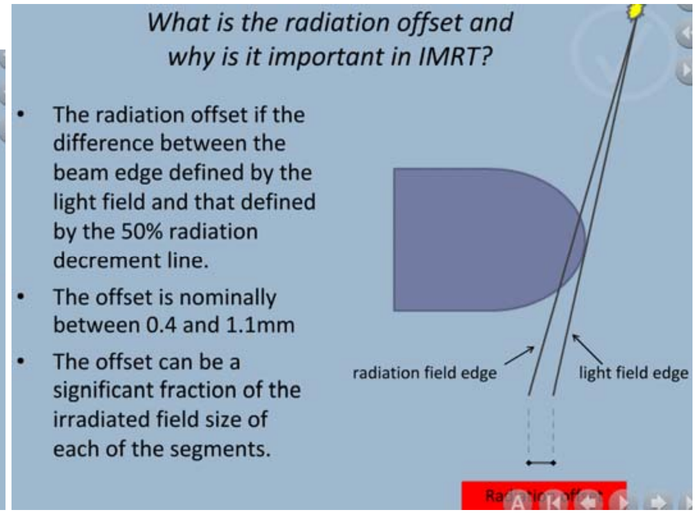
Relative constant penumbra: There is a slight offset between light field and radiation (light field underestimates radiation field by 0.5 to 1.2 mm per side), but with the rounded end design, this offset is approximately constant so it can be handled by treatment planning system.

DIS: penumbra can be larger than that of a straight/divergent leaf edge, and light field edge is different from 50% radiation field edge. The radiation offset is the difference between the beam edge defined by the light field and that defined by the 50% radiation decrement line. The offset is nominally between 0.5 and 1.2 mm. The offset can be a significant fraction of the irradiated field size of each of the segments. (in addition to leakage through the rounded Varian leaf ends, there is also a minimum separation of ~0.5mm to minimize opposing leaf collisions).



Dose profile for 10×10 cm^2 MLC compared with a collimated 10×10 cm^2 field across a Varian rounded leaf end MLC at d_{max} in a 6 MV photon field. Note how the MLC projects a wider profile and a broader penumbra due to rounded end leaf transmission. The leakage in the tail of the MLC penumbra is also higher than that under the jaw. Note only half of the symmetric profile is shown; also, the jaws were set at 30×30 cm^2 for data collection when the MLC was set at 10×10 cm^2.

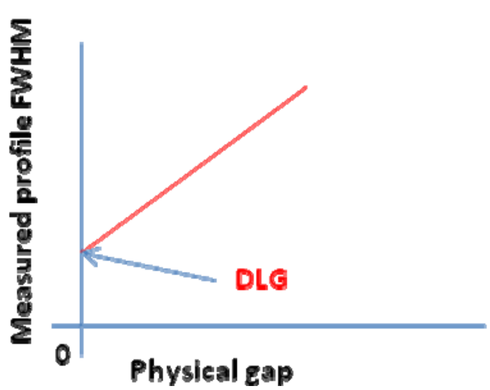
- (MLC offset)We also talked about Radiation/Light field offset, what its value typically was, how you measured the dosimetric leaf gap?



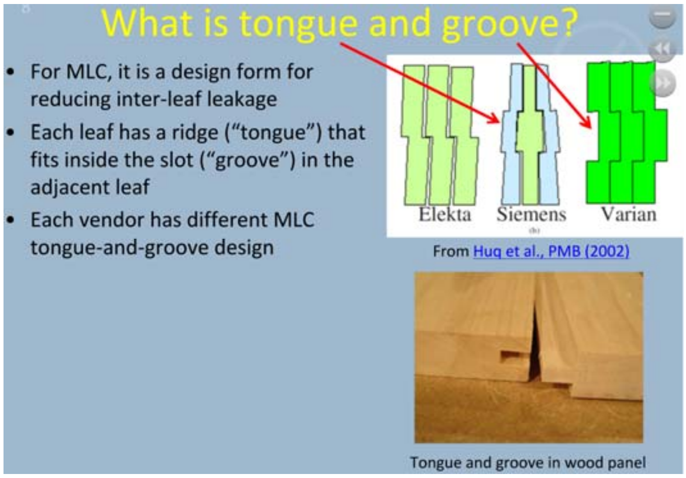
1 mm off for MLC can possibly induce up to 20% dosimetric error within the target volume for 1 x 1 cm field size (Kung et al. Med. Phys. 27, 1617, 2000)

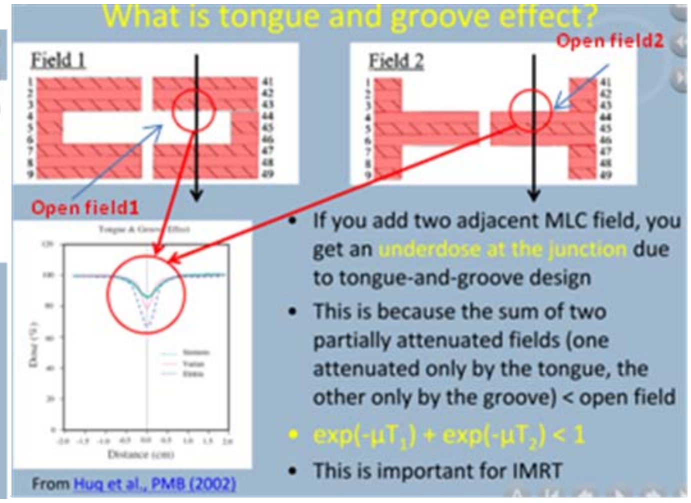
Provide a LAYMAN'S version of MLC offset determination.

Picture two opposing "square" leaves situated such that there is a 2 cm gap between them. If you put a chamber underneath the open area you will obtain a dose profile. Ideally, it will look like a square. In reality, it will show some broadening. The broadening "worsens" for rounded leaf ends. What a physicist must do is make a plot of the actual physical gap between the leaf ends (x-axis) vs. the ensuing FWHM of the dose profile (y-axis). For each data point, the leaves will be brought closer and closer in order to extrapolate the FWHM at "0" physical gap. This is the MLC offset, or "leaf gap value". It is a theoretical parameter of the MLC that must be entered into the TPS prior to commissioning. Typical values are around 4 – 7 mm.



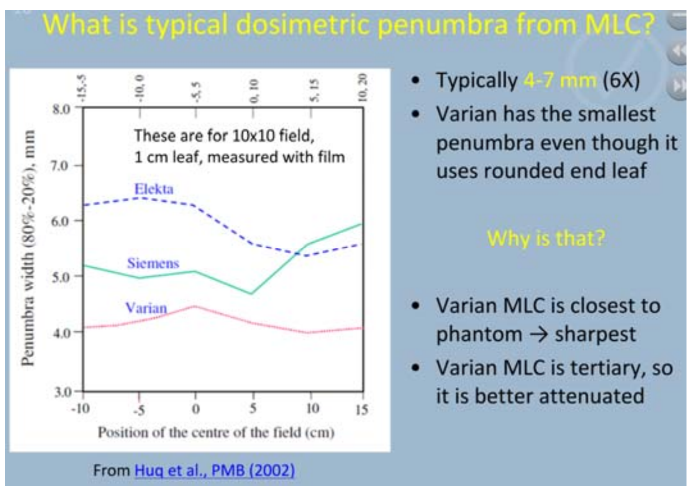
What is tongue and groove?





The above tong-and-grove shows that we are supposed to get combination of the 2 openfield with flat dose distribution. However, due to the attenuation by tongue from 1 field and the groove from another, we see the underdose effect at the field junction.

Discuss dosimetric properties of MLCs for beam modeling. What are the advantages/ disadvantages for each? Different types, penumbra, transmission, etc



The typical dosimetric penumbra from MLC is 4-7mm (6x), and Varian has the smallest penumbra even though it uses rounded end leaf. It is because Varian MLC is tertiary close to the target (small geometric penumbra), and it is better attenuated (small transmission penumbra).

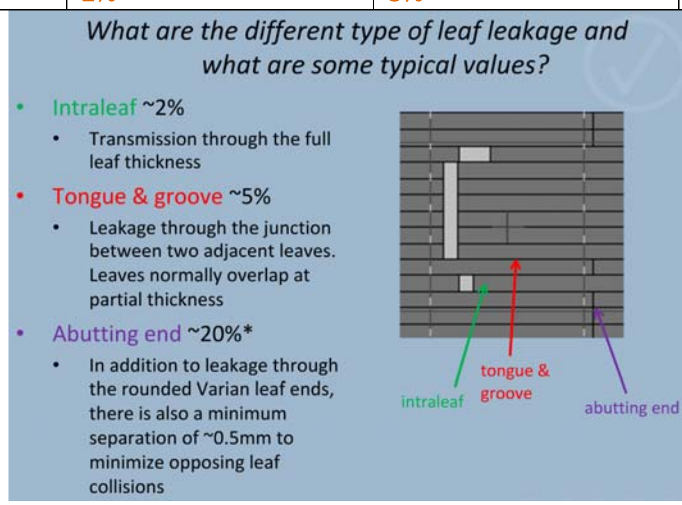
- What are they made of? What's the transmission of a leaf? What's the transmission between leaves? What's the tolerance of the MLC leakage? He wanted to know about leakage and what % of the CAX dose they typically were.

MLC are constructed from tungsten heavy alloys (WHA).

(Metcalf p 296): For upper or lower jaw replacement MLC (Siemens & Elekta), transmission requirements are the same as for standard collimators (< 2%){the secondary Jaw usually has transmission about 0.4% and 8 cm in thickness, MetCalf p34}. For tertiary MLC (Varian), transmission requirements are the same as for custom blocks (<5%). However, the leaf thickness should provide adequate attenuation to compensate for interleaf transmission.

Transmission Summary (http://www.aapm.org/meetings/02AM/pdf/8331-768.pdf)

	Intra	Inter	Abutting end
Elekta	2% if + backup jaw 0.5%	5%	50%
Siemens	1%	1.5%	
Varian	2%	3%	20%



Summary: Intraleaf ~2%, tongue & groove ~ 5%, abutting end ~20%

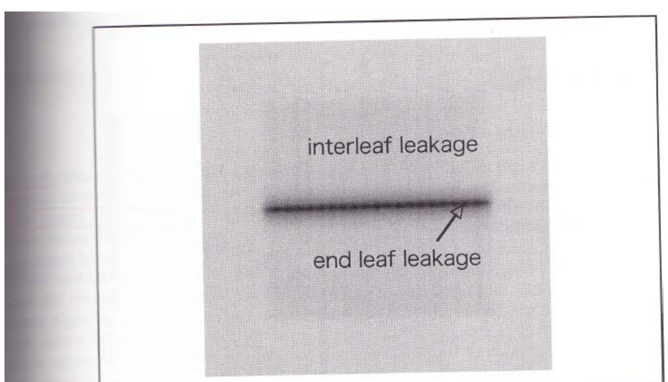


Figure 4.35: Dosimetry film showing end leaf leakage under a Varian MLC; note this leakage is about 30%, but in clinical treatments this is usually avoided by jaw shielding.

Transmission through the leaves vs blocks?

- Cerrobend transmission is about 5HVL, 5% (Kahn p274), & common thickness for cerroband is 7.5 cm. The transferring factor of the thickness between cerrobend and lead is 1.21.

- MLC transmission (intraleaf) is about 2% , so MLC is better than block for the leakage dose, but block has smaller penumbra due to the distance of block close to the target

What is the main ideas and procedures are associated with MLC acceptance, commissioning, & QA?

(DABR P511-514 from AAPM)

1. Alignment of mechanical & optical axes:
2. Leaf positioning test as a function of gantry and collimator angle
3. Transmission characteristics
4. Dosimetric considerations with respect to the TPS, ex: DLG
5. Data transfer
6. Reproducibility of field shape
7. Leaf speed

Acceptance Testing, Commissioning and Quality Assurance

- Alignment of mechanical and optical axes
- Leaf position calibration, leaf travel characteristics, as a function of collimator and gantry position
- "Follower" jaw calibration
- Transmission characteristics
- Interlocks
- Field shaping software, data transfer, reproduction of standard shapes
- Dosimetric comparison with treatment planning system

- (2006) What is your monthly MLC QA? What about your IMRT QA?

Uncertainty of 1-2mm is not an issue to 3D CRT, but is a problem for IMRT. For small IMRT fields, a small change in gap size can impact output by several percent. MLC accuracy is one of the most important topics for effective IMRT. Issues to be considered for MLC accuracy: leaf leakages, leaf position accuracy, light field edge vs radiation field edge, small MU segments effect and QAs for MLC accuracy. MLC leakage can be minimized by letting backup jaws following each IMRT segment (Varian does not, Siemens/Elekta do).

Varian uses an MLC lookup table to correct the mechanical leaf position to the light field position. MLC controller compares positions of all leaves and dose fraction delivered for given position with the plan (clinic console communicated every 50 ms with the MLC controller).

Monthly MLC QA:

Picket fence (check wepassed): Verifies leaf position and carriage movement accuracy and calibrations, Involves 8 consecutive movements of a 5-cm wide rectangular field (requires carriage motion), 1-mm strips at regular intervals, Visual inspection can detect improper positioning to a precision of about 0.2 mm. Match lines between 5-cm wide fields should be straight and approx equal in intensity. This pattern, when delivered properly, results in a series of 1mm vertical match lines that are a fixed distance apart, straight, of equal intensity. The test is considered passed if the match lines satisfy the above criteria to within 1mm.

Synchronized segmented strips: Verifies accuracy and calibration of leaf position and carriage movement when some adjacent leaf pairs are closed during beam delivery; Detects possible effects of inter-leaf friction on leaf positioning and ability of leaves to interdigitate; Involves 6 consecutive movements of a 4 x 24 cm^2 rectangular field; Each rectangular field is divided into a series of horizontal strips; Leaves between strips remain closed during irradiation; Precision of 0.5 mm. Match lines between 4-cm wide fields should be straight and approx equal in intensity; Match lines should appear at -12.0, -8.0, -4.0, 0.0, 4.0, 8.0, and 12.0 cm from field center (±1 mm); Intensity of exposed strips should be uniform, and non-exposed strips should be clear without exposure.

Continuous stripes(mainly for DMLC): Verifies accuracy and calibration of leaf positioning, stability of leaf speed, possible effects of interleaf friction, and possible effects of finite leaf acceleration and deceleration; Single file contains a 10 x 40 cm2 rectangular field with 5 match-lines of 1-mm width; A stripe of uniform intensity is produced by constant motion of a leaf pair; If speeds of both leaves are stable, delivered intensity is uniform; Precision of 1 mm. Intensities of exposed match lines should be uniform, and non-exposed vertical stripes should be clear without exposure; Match lines should be straight.

TG142 MLC QA

TABLE V. Multileaf collimation (with differentiation of IMRT vs non-IMRT machines).

Procedure	Tolerance
Weekly (IMRT machines)	
Qualitative test (i.e., matched segments, aka "picket fence")	Visual inspection for discernable deviations such as an increase in interleaf transmission
Monthly	
Setting vs radiation field for two patterns (non-IMRT)	2 mm
Backup diaphragm settings (Elekta only)	2 mm
Travel speed (IMRT)	Loss of leaf speed >0.5 cm/s
Leaf position accuracy (IMRT)	1 mm for leaf positions of an IMRT field for four cardinal gantry angles. (*Picket fence* test may be used, test depends on clinical planning-segment size)
Annually	
MLC transmission (average of leaf and interleaf transmission), all energies	±0.5% from baseline
Leaf position repeatability	±1.0 mm
MLC spoke shot	≤1.0 mm radius
Coincidence of light field and x-ray field (all energies)	±2.0 mm
Segmental IMRT (step and shoot) test	<0.35 cm max. error RMS, 95% of error counts <0.35 cm
Moving window IMRT (four cardinal gantry angles)	<0.35 cm max. error RMS, 95% of error counts <0.35 cm

Highlight is the QA performed in Penn, we do MLC spoke shot with collimator rotation.

What are some of the methods employed by the MLC control system to verify proper leaf position?

- Motor encoder
  - The motion of each leaf is tracked by encoders associated with each individual motor (300 motor counts = 1mm leaf movement projected to isocenter)
- Resistance band
  - A variable resistance signal is generated based upon the position of a "contact ball" attached to each leaf.
- Optical beam during initialization
  - During MLC initialization the motors drive the leaves and carriages through a specific set of positions as a form of calibration. Light beams and receptors are placed at critical locations within the MLC structure to confirm appropriate alignment of all leaves throughout this calibration exercise.

What is a log file and what can you do with it?

- A log file is a record of the actual dose fraction versus actual leaf position for an IMRT or dynamic arc treatment.
  - For Varian MLC, these positions are recorded every 50ms
  - From this data you can determine the difference between the prescribed leaf position versus the actual leaf position.
- The log file provides an auditable record (if saved) and can be used for MLC diagnostics or pre-treatment QA.
  - In the event of an MLC malfunction, the log file may be used to reconstruct dose delivered to the patient
  - By evaluating the differences between prescribed and actual leaf positions during test pattern deliveries over time, one can determine which motors are diminishing in performance and schedule maintenance/replacement.
  - Software has been developed to allow reconstruction of fluence from log file information and compare it to prescribed fluence as a form of pre-treatment QA.

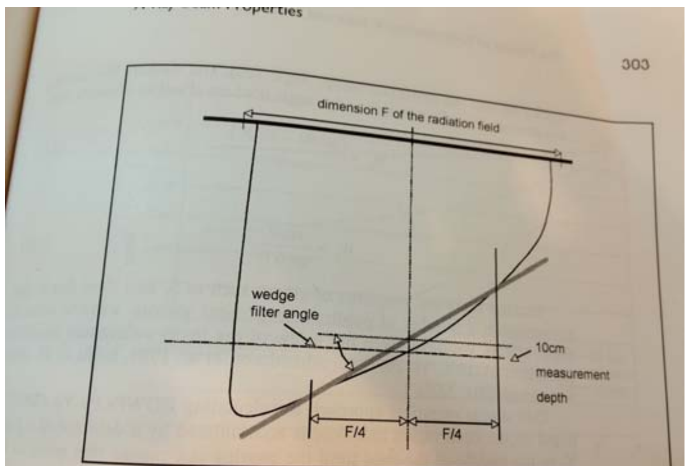
MLC leaf speed (<2.7cm/s) and gantry speed (65s in one rotation), according to Ling et al.

- **(Wedge)** Static, universal and dynamic wedge. What are they Clinical application? Pros and cons of each.

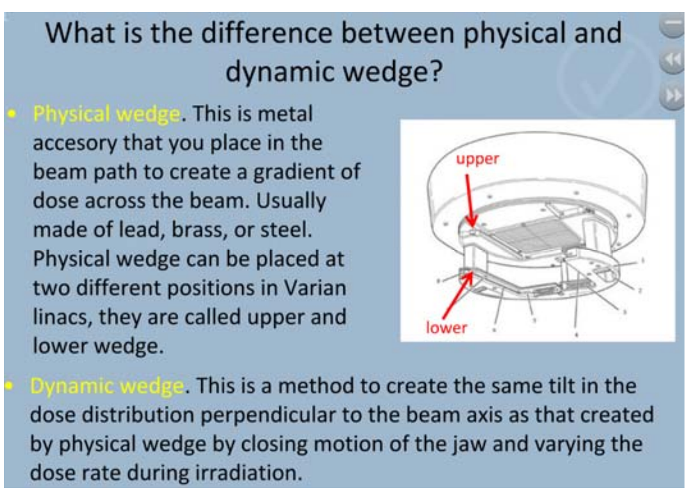
  Wedge angle: The angle through which an isodose curve is titled at the central ray of a beam at a specified depth, currently the depth is 10 cm (khan sec. 11.4.a). Depending on the vendor, Varian and Siemens define the **wedge angle at 10 cm**. One should know the **wedge angle** is the angle between the iso dose line of the wedge field and the **normal** to the CAX.

  Wedge factor: the ratio of dose at a specified depth (usually 10 cm) on the central axis with the wedge in the beam to the dose under the same conditions without the wedge. This factor is used in MU calculations to compensate for the reduction in beam transmission produced by the wedge.

  For MU calculation, if the machine is calibrated at d_{max}, it is suggested by Kahn & MetCalf to measure the wedge factor at deeper depth such as 10 cm to avoid the beam hardening & e contamination, and then use PDD to transfer the wedge factor to d_{max}.



ure 4.37: Wedge angle convention which allows for curved isodoses at reference depth of 10 cm.



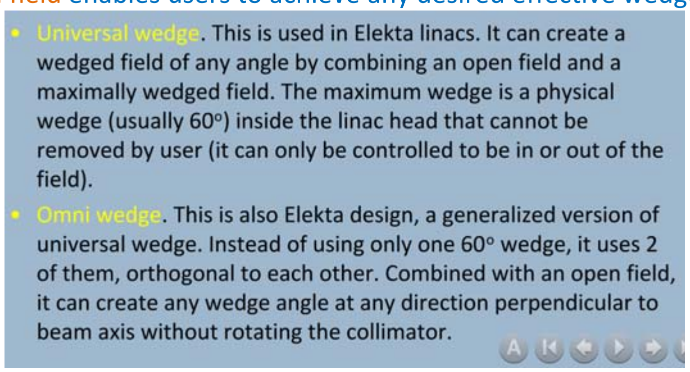
Physical wedges (removable wedges), are individually designed metal wedges which are used to produce a defined (tilted) nonuniform dose distribution at a specific depth. The physical wedge can be inserted into treatment head externally or internally. The effect of the uncertainty in positioning the wedge in the exact location needed for reproducing the "tilted" dose distribution is greater for the internally positioned wedge than the external wedge. This is because the internal wedge is much closer to the target, and therefore a small error in positioning may result in a large error in the isodose distribution. Depending on depth and field size

Soft wedge (Dynamic) mimics the tilting isodose line of the physical wedge by moving only one collimator jaw, usually a Y-jaw, while keeping the other Y-jaw stationary during beam on time.

> Enhanced dynamic wedge (EDW) – Varian varying jaw speed and dose rate, Varian EDW wedge traveling direction Y jaw is the same as MLC leaf traveling direction, so we can't use MLC & wedge simultaneously for the same field.
> EDW can travel from 20 to -10cm. Depending on field size only.
>
> Virtual wedge (VW) – Siemens varying only the jaw speed the dose rate is based on a built-in analytical function depends on the required effective wedge angle. VW can be used either in X or Y jaw direction. Not Depend on depth or field size.

(check Gibbons AAPM proceeding paper)

Omni universal wedge, used in Elekta, is a built-in 60 degree motorized physical wedge, which when combined with an open field enables users to achieve any desired effective wedge angle up to 60 degree.



(Universal wedge vs. Dynamic wedge)
Elekta Omni wedge can create any wedge angle at any direction perpendicular to beam axis without rotating the collimator. Varian & Siemens can only generate the wedge angle along the jaw direction.

(Haibo note, Greens p86): As a single universal wedge has to cover all possible wedge angle dose distributions, it must be significantly thicker (on the central axis) than any of the individual wedges it replaces and will therefore have a higher wedge attenuation factor.
For dynamic wedge, as the wedge effect is not produced by differential attenuation through a filter the beam is not subject to changes in energy as the case for physical wedge filters.

There are 2 main uses of wedges for clinic (Podgorsak p199):

(1). Wedges can be used to compensate for a sloping tissue surface, as for example, in nasopharyngeal treatments where wedges are used to compensate for decreased thickness anteriorly, as shown in Fig. 7.16. Part (a) shows two wedged beams in a parallel-opposed configuration with the wedges used to compensate for missing tissue. (2). Part (b) shows two wedged beams at 90^{o} to one another with the wedges compensating for the hot-spot near the surface

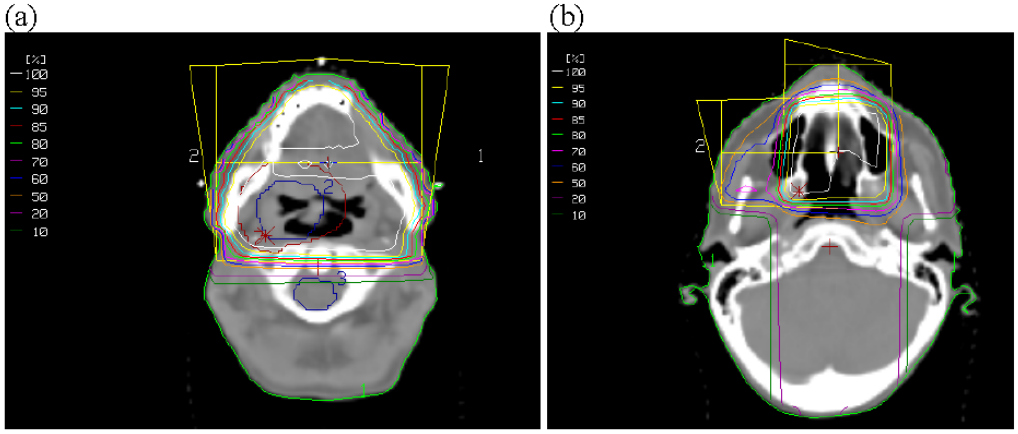
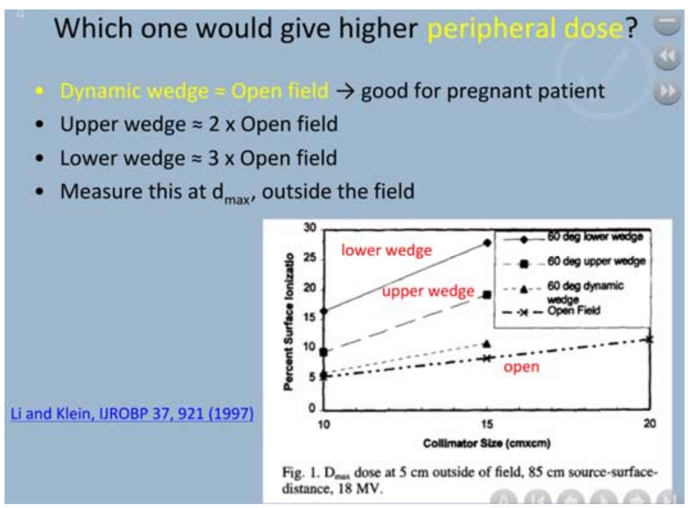


FIG. 7.16. Treatment plans illustrating two uses of wedge filters. In (a) two 15° wedges are used to compensate for the decreased thickness anteriorly. In (b) a wedged pair of beams is used to compensate for the hot spot that would be produced, with a pair of open beams at 90° to each other.



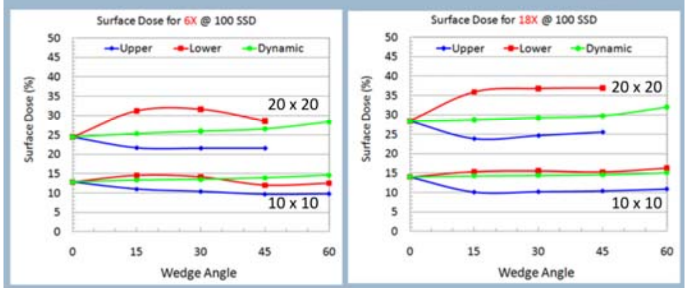
Peripheral dose refers to the ionization "outside" of the field. Measurements are usually taken 5 cm away from the field borders and at a depth of dmax. The trend between the various wedges is as follows:

Which one would give higher surface dose?

- Magnitude: Dynamic wedge ≈ Upper wedge ≈ Lower wedge
  - 10x10: surface dose ≈ 10% (6X) and ≈ 15% (18X)
  - 20x20: surface dose ≈ 25% (6X) and ≈ 30% (18X)
- Trend: Upper wedge < Dynamic Wedge < Lower wedge
- Surface dose from upper wedge < open field
- Surface dose ↑ with energy (more electrons generated at head)
- Surface dose ↑ with field size (more scattering sources)
- Surface dose ↓ with SSD (inverse square effect)

Surface Dose from Wedged Field

(0 is for open field)



Li and Klein, IJROBP 37, 921 (1997)

What are some of the advantages and disadvantages of dynamic wedge versus hard wedges?

- Advantages of dynamic wedge
  - Larger field size
  - Greater number of wedge angles
  - Reduced scatter
  - No room entry required for wedge changes
- Disadvantages of dynamic wedge
  - Additional complexity and mode of failure
  - Less intuitive (ex: heels up for breast tangents… easy to discern with hard wedges), therefore mistakes/errors less likely to be noticed.

Dis: if a clinical does not uniformly employ non-physical wedge for all the machine, it can create confusion and difficulties when sawpping pts from 1 linac to another.

Adv: Dynamic wedge is much time efficiency compared to physical wedge + less peripheral(scattered) dose, ex: reducing the radiation-induced malignancy in the contralateral breast during the breast treatment.

Does the wedge affect the profile in the non-wedged direction relative to open field?

- No effect for dynamic wedge perpendicular to the wedge direction
- For physical wedge, off-axis dose ↓ relative to open field because:
  - Beam hardening effect from the physical wedge
  - The off-axis pencil beam has to travel longer distance inside the wedge (oblique path)

- Question drifted to Dynamic wedge, Do you measure all possible angles? Are they field size dependent?

We use Varian; during commissioning, the wedge factors for 10, 15, 20, 25, 30, 45, 60 were measured for the field size required in the eclipse. In addition to the wedge factors, we also measure the profile and the depth dose.

During annual, we spot check 10 & 60 degree wedge factor for both photon energy & 3 field size 5, 10, 20 cm

- Question on either VW or EDW (depending what you use). How do you measure wedge factor, how is it used in your hand calculations?

Measure Wedge factor: the ratio of dose at a specified depth (usually 10 cm) on the central axis with the wedge in the beam to the dose under the same conditions without the wedge.

1. Center the chamber in the beam: Place detector axis along nonwedged direction by taking readings with a 60° wedge at two collimator angles 180° apart. If the chamber is centered, these two readings should be close.
2. Once the detector is centered in the beam, the wedge factor is taken as the average of the two wedge orientation (180° apart) readings divided by the open field reading at a single collimator angle.

This factor is used in MU calculations to compensate for the reduction in beam transmission produced by the wedge.

For MU calculation, if the machine is calibrated at d_{max}, it is suggested by Kahn & MetCalf to measure the wedge factor at deeper depth such as 10 cm to avoid the beam hardening & e contamination, and then use PDD to transfer the wedge factor to d_{max}. Since our machine is calibrated at SSD = 90 cm and d = 10 cm, we don't need to transfer our wedge factor to d_{max}.

What is STT table? How many angles does it have?

The heart of the dynamic wedge modality is the segmented treatment table, or STT, which governs the position of the jaws with respect to the number of delivered monitor units (cumulated MU). The dynamic wedge STT specifies the moving jaw position in equally spaced steps as a function of the cumulative fractional dose; beginning with the open field size and ending with the jaws in the final ''closed'' position. Varian STT has 7 angles, 10, 15, 20, 25, 30, 45, & 60.
Stored within the accelerator's computer are STTs for each available energy, field size, and wedge angle.

For EDW, the wedge factor is field size dependent, & hence WF table vs. FS have to be issued. EDWF are essentially a composite of open field and sweeping collimator effects. The tabulation of how many MUs have been delivered at each point during the travel of the jaw is called the golden segmented treatment table (GSTT). Current Varian linacs jaw for EDW can travel from 20 cm off-axis to a point 10 cm beyond CAX. The GSTT is defined such that a 60-degree wedged dose distribution results from the linac jaws moving w dose delivery conforming to this table.

The EDW, unlike its predecessor, is based on the concept of a universal wedge in which an isodose distribution from an intermediate size wedge can be produced by the linear combination of the distributions from an open field and a maximum 60° wedge field. Each energy has a unique GSTT.

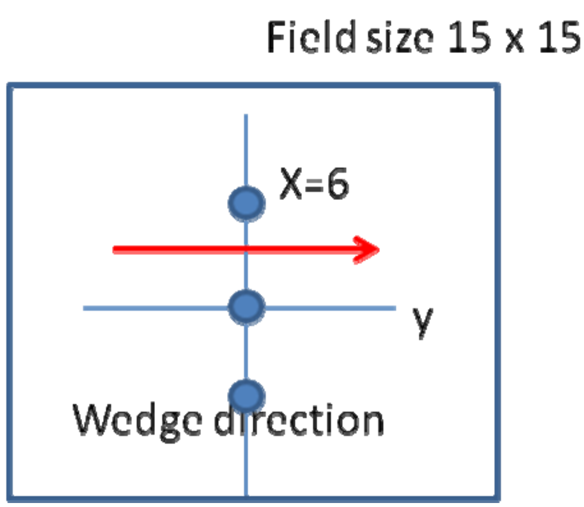
How to commissioning? Acceptance test? Do you verify your STT table?

AAA only requires measurement for hard wedge and motorized wedge (Elekta universal wedge), so for EDW, there is no need to perform measurement for beam data configuration. However, during commissioning, we need to check

What are the primary goals in the commissioning of a dynamic wedge system?

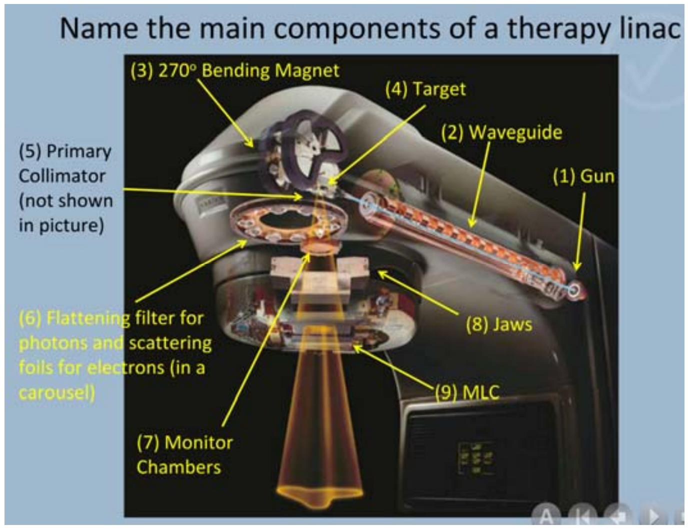
1. Confirm the wedge angle is accurate at depth of interest (10cm) and reasonable at other clinically relevant depths
2. Confirm wedge orientation is accurate (in/out/right/left)
3. Confirm dependence of output and profile on field size and depth is accurately modeled in the radiation therapy planning system

During commissioning, we did benchmark tests for all the wedge angle at (1). (x = 0, y=0, z=0)10 cm depth & 10 x 10 cm field size, & at 20 cm depth (with (2) x = -6, (3) 0, & (4). 6 cm for y = 0, z = 0 location with field size 15 x15 cm). The tests are to check the output dose rate cGy/MU consistent with the TPS (not checking the wedge factor).



C5-B (Linac)

- **(general)** Pic of linac ? identify 5 structures
- Given picture of accelerator (I believe it was the cutaway picture from the Varian sales brochure). know about each part from e- gun to accessory mount. DETAILED description and function of each (e- gun, accelerator structure, bending magnet, target, flattening filter, primary and secondary collimators, etc).



Linac components:

Electron gun:

generates electrons through thermionic emission and injects pulses of electrons to electron accelerator

Accelerating waveguide:

1. Evacuated metallic structure used to accelerate the e to the desired energy
2. By sending high-power microwaves using a klystron or magnetron into the accelerator waveguide, the microwave fields induce an electric current within the guide wall, and the current generates an electric field. If electrons are introduced into one end of the guide, the electric field will exert a force on the electrons and accelerate them.
3. Traveling or standing wave; standing is shorter;
4. most operates at S band (3GHz); compact waveguide operates at X band (9GHz);
5. The high vacuum (10^{-6} Torr) maintained inside the waveguide is to prevent electron loss and arcing by interacting with air particles
6. To achieve the high electrical conductivity at microwave frequencies, the accelerating guide is usually made of copper.
7. A waveguide, which is a completely hollow structure, is not suitable for accelerating electrons because the microwaves are transmitted much faster than the injected electrons. Hence, the advancing microwave fields are slowed by introducing into the waveguide a series of disks (irises) with a hole in the center of each one. The guide is therefore divided into a series of cavities.

Bending magnet:

1. After the electrons are accelerated through the waveguide, they are focused and bent to the desired direction using magnets. Except for some single low-energy accelerators (e.g., Varian 600C), which direct the electrons to the target without the use of a bending magnet.

2. Helps to focus the beam after any positional or spectral spread.

Target:

1. To generate a Bremsstrahlung x-ray beam, a thick transmission target is usually used. The thickness of the target is sufficient to stop all incident electrons. The target is made of high-Z materials (usually tungsten alloy) to increase the efficiency of the Bremsstrahlung yield.
2. Transmission target for MV vs. reflective target for kV; conversion efficiency is on the order of 10-20%, contrast this with <1% efficiency for kV X-ray, cooling is less an issue for MV target than for kV target;

Primary collimator:

1. Cone shape collimator; Collimates the beam coming out of target to a circular beam forming 50 cm diameter circle at ISO
2. Minimize side leakage to 0.1%

a. Flattening filter for photon mode on a carousel:

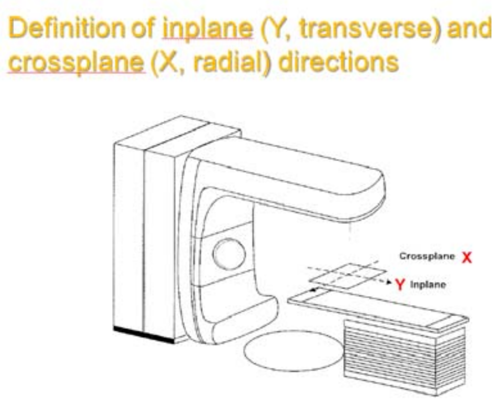
1. Cone shaped to create flat beam at specific depth, usually 10 cm(reduce photon fluence at center);
2. should not use high-Z material because it differentially filter out the high energy photons and beam is softened; a small change in x-ray energy cause the beam to be either over or under flattened; usually made of medium-Z material, such as Al.
3. Each photon mode has its own flatten filter

b. Scattering foils for electrons mode on a carousel:

1. Each electron energy has its own foil
2. a dual scattering foil system is often used
   - 1st scattering foil produces a broad electron beam by scattering the beam
   - 2nd scattering foil flattens the resulting electron beam by further scattering the beam

Monitor chambers:

2 monitor chamber to monitor output dose, dose rate, calibration, beam symmetry in radial and transverse direction.



Secondary jaws:

The higher the jaw position, the larger its penumbra; leakage max should be less than 2% by IEC. Usually < 0.5%;

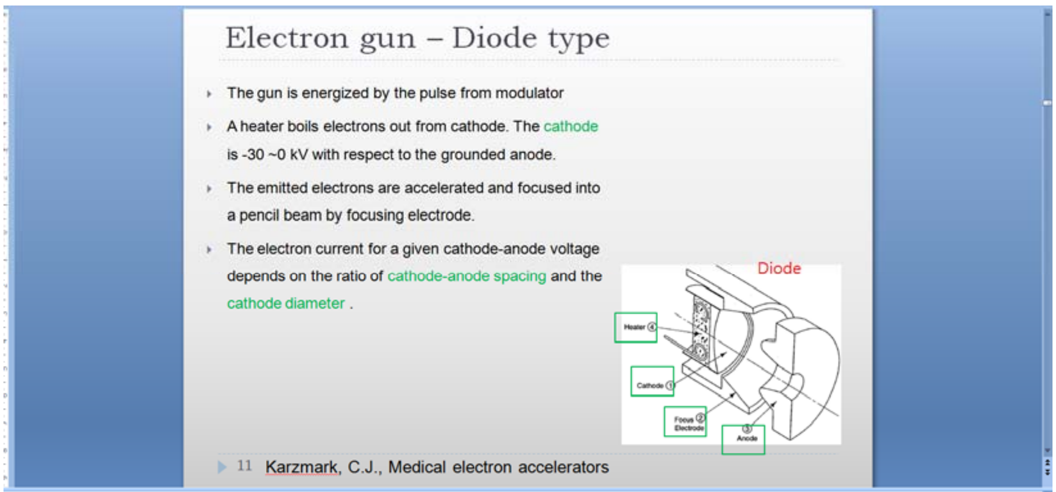
Collimator position and indicator maximum error should be a fraction of mm; the geometric penumbra of the inner jaws is larger than outer jaw

MLC

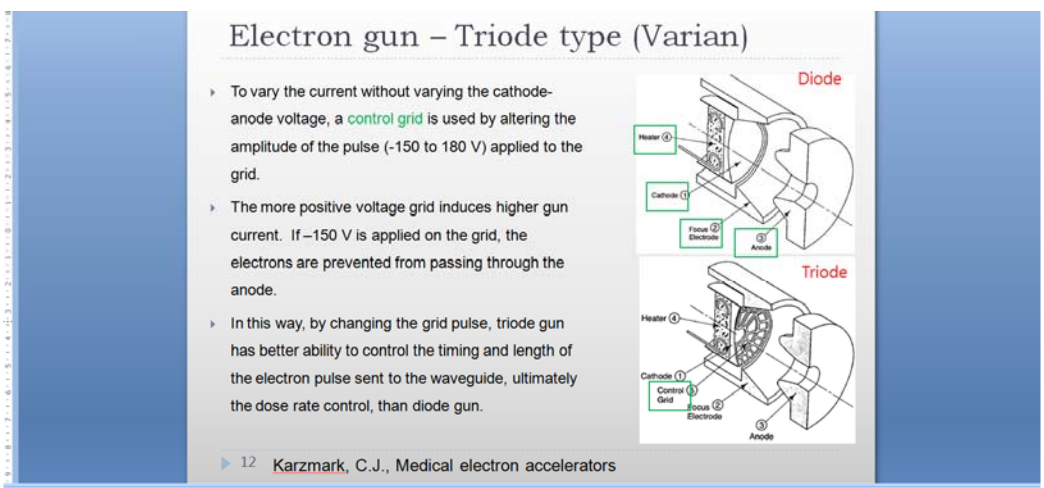
Beam-defining aperture closest to patient to make sharpest beam; leakage max should be less than 5%, usually < 2% intraleaf and < 5% interleaf).

- LINAC Functional Block Diagram (Karzmark and Morton's Book pg. 35). How do you define energy?

(Electron gun) - triode diode design and Know which one would be better for single and dual energy accelerators? Also identify all the parts of the gun (heating coils, grid, anode, cathode, etc.) that are marked, what is each one's purpose?



The emitted electrons are accelerated toward the anode, and focused into a pencil beam by a cone-shaped focusing electrode to pass through the beam hole in the anode.

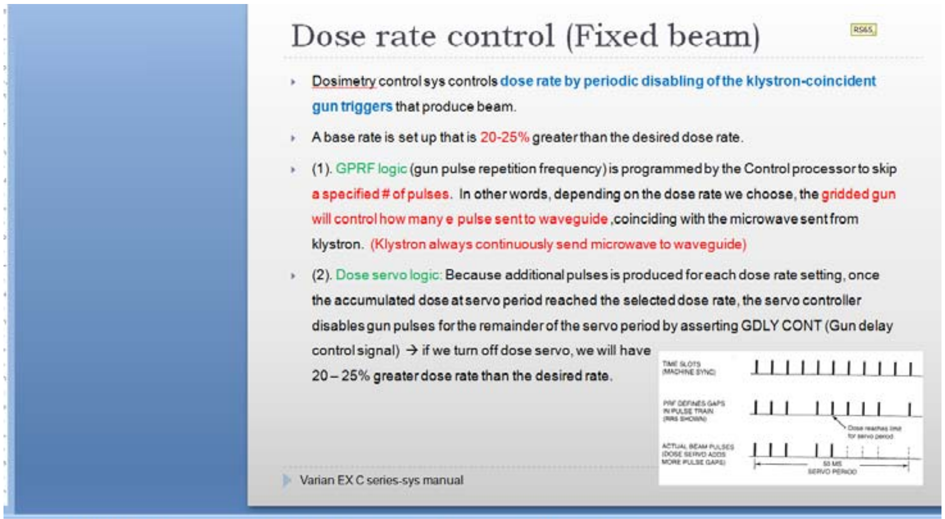


For diode gun, the microwave and e pulses have to be exactly in phase, but with triode gun can allow slightly delay of the injected electron. In this case, it allows accelerator to fill with microwaves before injected e gets in, and it can ensure all the electrons accelerated in the same energy.

How do you change the dose rate on the LINAC?

Varian has fixed pulse rate (energized accelerating cavity), and dose rate modulation is accomplished by varying how many of the pulses coincide with electron-loading of the accelerating cavity by the gridded gun.

Varian linac employs a triode electron gun system which generates and accelerates electrons for each pulse regardless of the dose rate selected. An electrified "grid" at the end of the electron gun is used to prevent the electrons passing through the accelerating cavity whenever an electron-loaded pulse is not required.

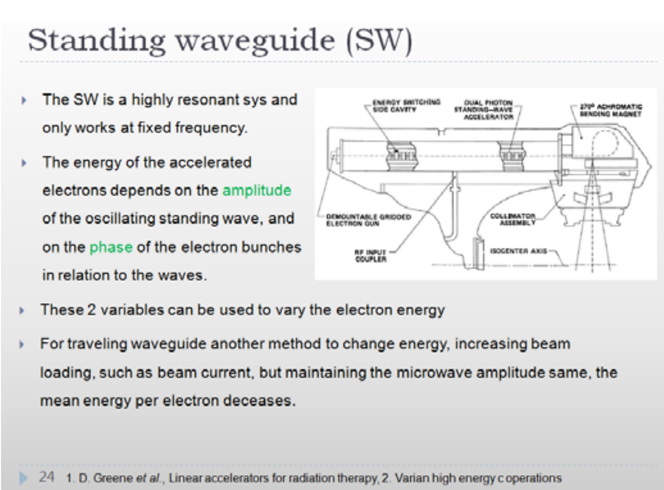


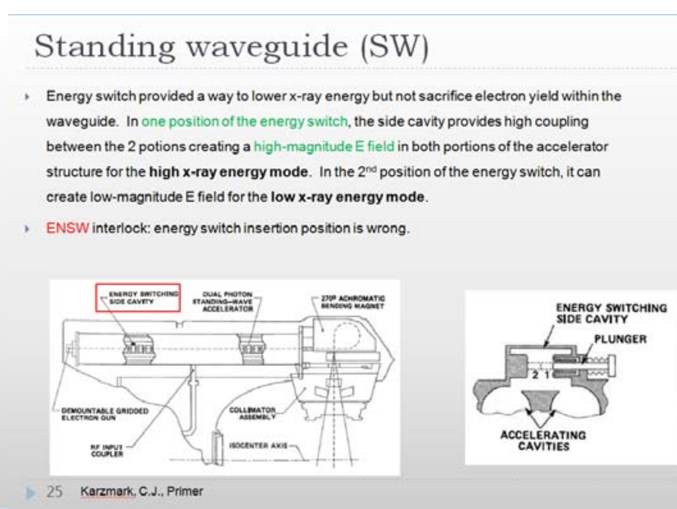
ex: 400 MU/min x-ray mode, 4 out of 6 pulses will be used to produce beam.
Order of centiMU ~per pulse

How do you define energy?

(**Primer 26-28** has very good explanation, DABR p93)
For dual energy machine, we can utilize either
(a) variable neighbor couplings to affect RF (energy switch used in standing wave guide Varian machine)
(b). phase switching in the accelerator field (standing wave guide) or
(c). beam loading in the gun current to provide the capability of continuously varying the e output energy from the linac without degrading the energy spectrum (Traveling waveguide).

Key point: Because the RF power is reflected back & forth in a standing wave structure, the 1st portion (gun end) senses and adjusts to the field in the 2nd portion (output end), and vice versa. Therefore, if we change the amplitude or phase of the E field at one end, it will change on another end.



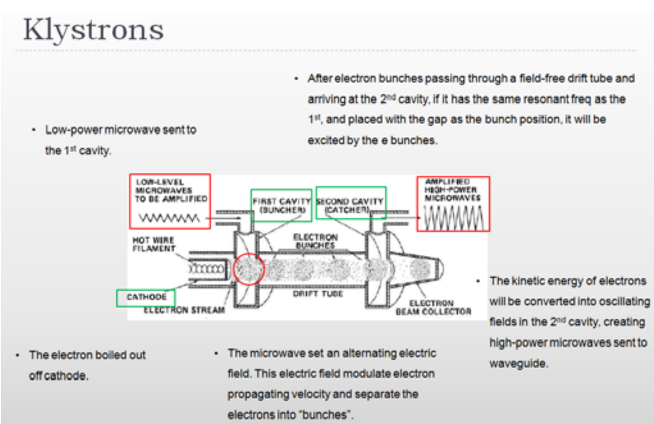


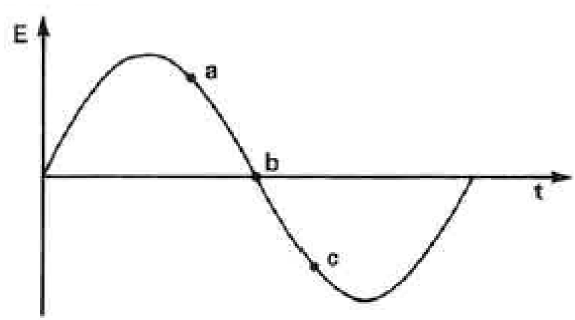
Standing wave guide only can work for a fixed freq

Know which one would be better for single and dual energy?
From the point (c), triode gun is able to control the beam loading (incident gun current) get into the waveguide. Essentially, the high energy x-ray mode requires light beam loading and the low energy x-ray mode requires heavy beam loading. (The average energy per electron is low if we have high current but keeping the same RF power input as a constant from Klystron or Magnetron)

(Haibo's note): Diode and triode type electron guns are used by different manufactures, as are a wide variety of types of thermionic cathode. During x-ray production, when beam currents are high enough to cause beam loading, the maximum energy to which electrons are accelerated in the waveguide can be controlled by regulating the beam current. A triode gun uses grid control of the electron beam current through the assembly, and therefore can use an indirectly heated cathode and still give very rapid regulation of the electron beam current. The grid is normally held sufficiently negative to the cathode to cut off the current to the anode, and thus the timing and magnitude of the current pulses injected into the accelerating guide are controlled by voltage pulses applied to the grid.

- **(Klystron important ! many questions related)**
  Picture of Klystron with lot of labels on it. (a more elaborate drawing than simple diagrams on textbooks) What's this (MicroWave amplifier) and how is it used?
  Know what the source is and that it required (a low MW oscillator source).
  Where is the source of electrons?
  How does it amplify RF power?
  Show where the input and output RF directions.





(review this slide using powerpoint which gives step by step)

Using the following as the correct step

- On the left is the cathode, the source of electrons for the klystron, which is given a negative pulse of voltage.
- This accelerates electrons into the first, or buncher cavity. The buncher cavity is energized by very low-power microwaves that set up alternating "E" fields across the gap between left and right cavity walls. Recall that it is the negative"E" field that accelerates the electrons. Those electrons that arrive early in the microwave cycle, at times between points a and b, encounter a retarding "E" lield and are slowed. The velocity of those electrons arriving at time b, when the

"E" field is zero, is not affected. Electrons arriving at later times, between points b and c, are speeded up by the negative "E" field. This causes the electron stream to form bunches. This process is called velocity modulation

- They pass along the drift tube. The second, or catcher cavity, has a resonance at the arrival frequency of the bunches. As the electron bunches leave the drift tube and traverse the catcher cavity gap, they generate a retarding "E" field by inducing charges on the ends of the cavity and thereby initiate an energy conversion process. By this process, much of the electron's kinetic energy of motion is converted to intense "E" fields in the second cavity, creating microwave power that is used to energize the linear accelerator structure.
- The residual beam energy that is not converted to microwave power is dissipated as heat in the electron beam collector on the far right. The heat is removed by the water cooling system.
- Such klystrons have 3 to 5 cavities and are used with high-energy linacs, e.g.,I8 MeV and above. The additional cavities improve high current bunching and increase microwave power amplification.

The oscillating field in the first cavity will cause electron bunches. At a distance the electrons will arrive in **bunches at a frequency** determined by the resonant frequency of the first cavity. If the second resonant cavity has the same frequency as the first, and is placed with its gap at the bunching position, it will be excited by the electron bunches arriving in resonance and the electron bunches will pass energy very efficiently to the oscillating field in the second cavity.

- The cathode/electron gun end is submerged into an oil filled tank to provide necessary electrical insulation. The electron first boiled out off cathode by heating the filament.

- The negative electric field accelerates the electron, and the positive field decelerates the electron.
- The 2nd cavity so called catcher cavity has the resonant frequency as the electron bunches.

- Bunch of electrons propagate through the klystron vacuum tube. The cavity of the tube is resonant with the propagating electron bunches. Therefore, the kinetic energy of the electron bunches is transferred to the output microwave in an electromagnetic energy form.

What effect does changing the distance between cavities have?
It will reduce the efficiency of ouput microwave generation.

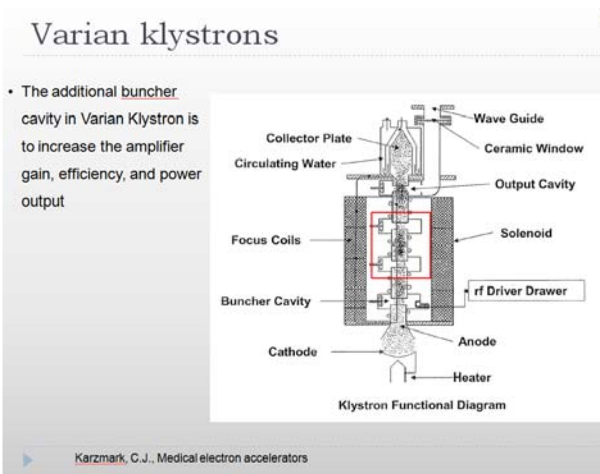
Is transmission guide (section?) filled? (me: this question shouldn't ask for the klystron drift tube, because klystron is vaccumed by an ion pump, see the detail klystron figure below)

The **transition section** are needed to connect components of different types. Because of the high electric field strengths in the waveguide sections connecting the major functional components, it is necessary to operate them under vacuum (low pressure) or high gas pressure to prevent voltage breakdown. The transition section between the magnetron and transmission guide, needs to be gas filled (nitrogen, Freon or **SF6**), to provide gas cooling for the glass output dome of the magnetron, and is operated at high pressure (2 atmospheric pressure) to prevent sparking. The external microwave load at the high-energy end of the accelerating waveguide also needs to be in a gas filled waveguide, the gas providing surface cooling for the dielectric load.

Additionally, all parts of the **electron beam transport** sys, including the e gun, the waveguide, & bending chamber, have to be operated under vacuum to prevent scattering of the e beams. Klystron is also vaccum see the following figure (klystron is with ion pump)

- o Have you seen your klystron? How big is it? What does it look like? Why cover it?

o



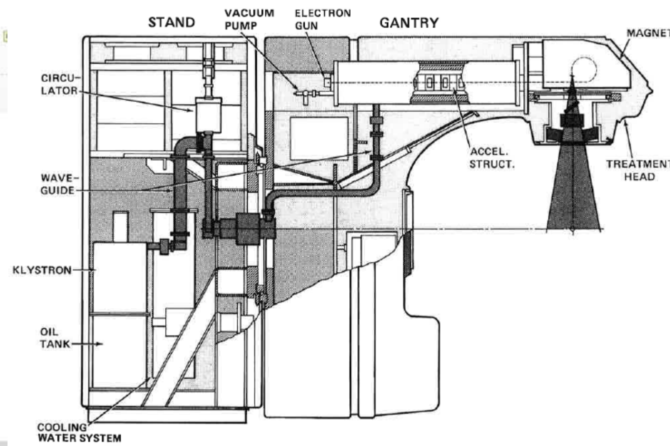
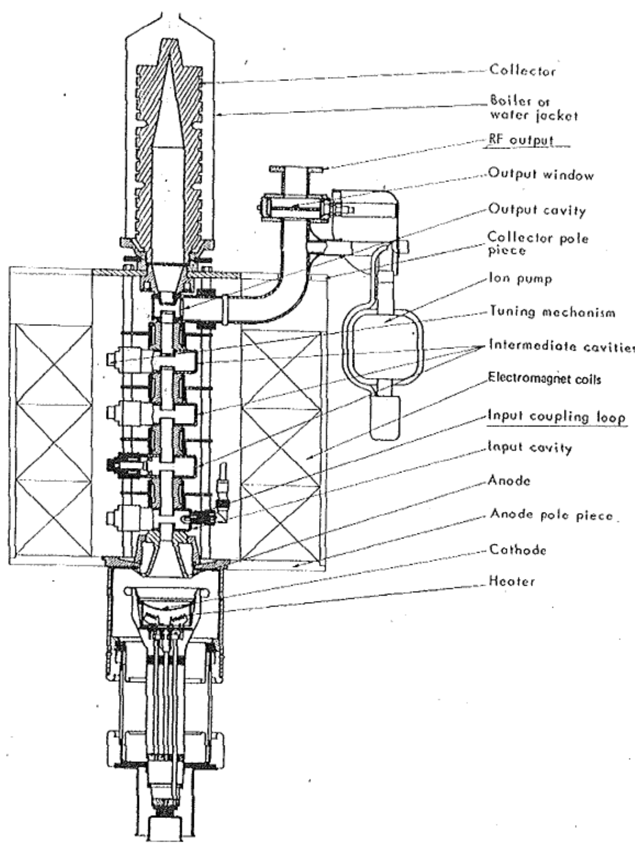


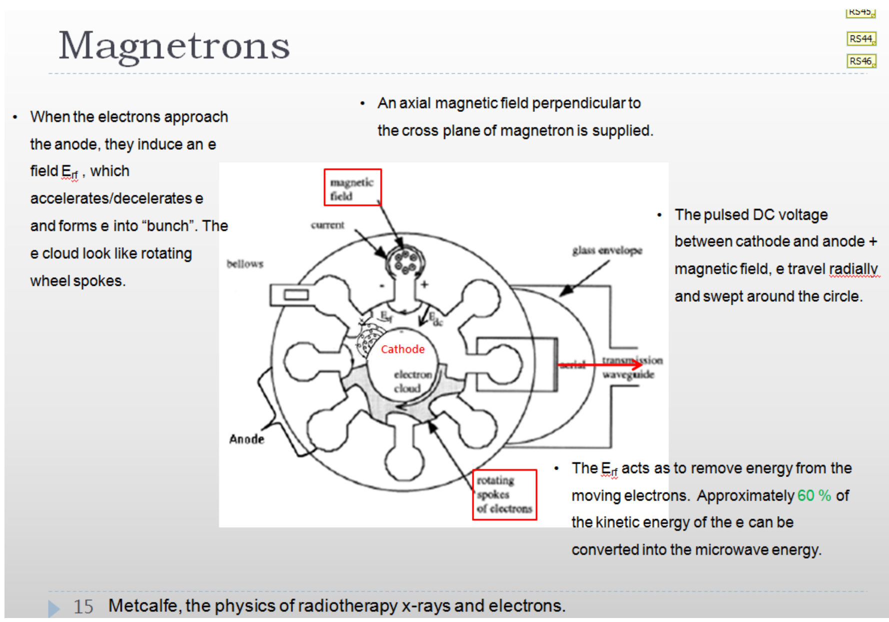
Figure 15. Schematic diagram of a high-energy radiotherapy linac (Clinac 18) identifying major components housed in the stand and gantry.

(Primer p13)The klystron is about **1 m** in length and sits **atop an oil-filled tank** with its cathode-electron gun portion submerged to provide the **requisite electrical insulation** (see above Figure)

Detailed Multi-Cavity Klystron Schematic:



- **(Magnetron)**A cross section image of a Magnetron; describe its components, how does it work? Where do you think the direction of the magnetic field is? What kind of power output in MW? What about the power output of Klystron in MW?
- Q5: Shown picture of magnetron. Discuss what it is, how it works etc? There was an arrow pointing to one of four blue dots in the space between the cathode and anode. I had no idea what it was.



A **bellows 風箱** is a device for delivering pressurized air in a controlled quantity to a controlled location.

The coaxial anode is surrounding the cathode, located close to the magnetron wall.
After the electrons are boiled out from the cathode, a pulsed DC voltage applied between the cathode and anode (from Pulse modulator), e travel radially along the opposite direction of the electric field E_{dc}, and the magnetic field exerts a magnetic force on these traveling electrons, and they tend to be swept around the circle.

When the electrons approach the anode, they induce an additional charge distribution shown on the anode poles and an electric field E_{rf}. In a manner similar to that in the catcher cavity in the klystron, the E_{rf} fields act to remove the energy from those moving electrons, and **the reduction of kinetic energy will be transferred as the high frequency microwave energy. In the process, approximately 60 % of the kinetic energy of the electron can be converted into the microwave energy. An output aerial is inserted into one of the cavities to transfer the microwave power from magnetron to waveguide**

An electron crossing the mouth of one of the anode cavities will start the system oscillating. Electrons circulate concentrically round the anode cathode space, and electrons were bunched together due to the oscillating cavities, and then space charge was formed and like a set of rotating wheel spokes. The spokes cross the mouths of successive cavities at times when they are decelerated, and the rotating electron gave energy to the oscillating cavities. The frequency can be varied slightly by moving the plunger P.

The **isolator** allows the passage of radiation from the magnetron, but presents a high impedance to reflected waves (basically prevent the wave reflected back to the magnetron). The isolator is designed to absorb energy and it is cooled by water circulation.

(Klystron vs. magnetron)

- What are the advantages and disadvantages of magnetrons versus klystrons? life-span, cost and size? What's your linac using? What is the frequency of the microwave?

Klystrons and Magnetrons

	Klystron	Magnetron
Characteristic	Amplifier with low-power microwave input	Self-oscillator, producing the microwave in response to a DC input
Application	High energy linac	Low energy linac
Output (s band, 3GHz, λ=10 cm)	5 – 20 MW	2 – 5 MW
Life time	10,000 hr **(5yr)**	2000 hr **(1yr)**
Temperature dependent	No	Yes
Dimension	Large	Small (can be mounted on gantry)
Stability, expense, complexity	More Stable, expensive, complicated	

The klystron output is 5 – 20 MW and Magnetron is 2 MW, 20 MW is from the AAPM review course.

The microwave frequency employed by medical linac is 3000 MHz in S Band. The reason to choose S Band frequency is the wavelength in the order of 10 cm, which is an appropriate length so that the accelerators components can be reasonably design and manufacture.

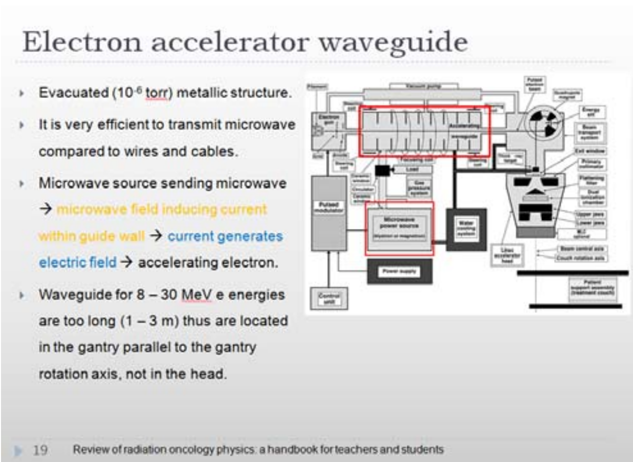
Varian uses Standing waveguide + klystron because the frequency and beam stability is more stable than traveling waveguide + magnetron (DABR P93)

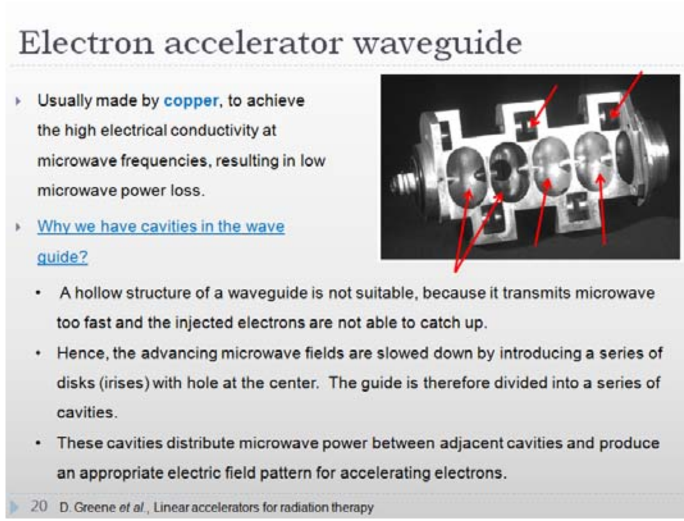
(Greens Ch3) For electron energies up to about 10 MeV, a magnetron operating at a peak power of 2.5-3 MW is used. Magnetron power up to 5 MW or klystron operating at peak power of 7 MW have been designed for higher energy. Magnetrons are physically smaller and operate at lower voltages so that they can be mounted on the rotating gantry of Linac. Klystrons are somewhat larger, operate at higher voltages and are mounted within a tank of insulating oil, which can't be mounted on the gantry.

(Green p34) There is a remarkable relationship between magnetron/klystron & waveguide. In **magnetron and klystron**, a high current of relatively low-energy electrons is used to excite oscillations in a set of coupled cavities. The energy from these cavities is then passed to the **accelerating waveguide** (again, essentially a set of coupled cavities), where it is used to accelerate a very small electron current to high energy.

- **Waveguide:** How about accelerating guide? What's the frequency and wavelength of the RF waves? What happens if the frequency is doubled – how does it change the design of accelerating waveguide? What's a competing design for RF source?
(This part check the we passed "standing wave")

- Explain how electrons are accelerated.





In the accelerators, it is responsible to speed up electrons to the desired energy, and these electrons can form prescribed treatment electron beam or induce X-ray beam.

Therefore, the stability and accuracy of the waveguides controlling the output electron energy is extremely important to the quality of patient treatment.

- By sending the high-power microwave using klystron or magnetron, into the guide, the microwave fields induce an electric current within the guide wall, and the current generates an electric field. If we input electrons from one end of the guide, the electric field would exert force on the electrons and accelerate them.

The length of waveguide can be 30 cm for a 4-MeV accelerator to 1 – 3 m for higher electron energy units.

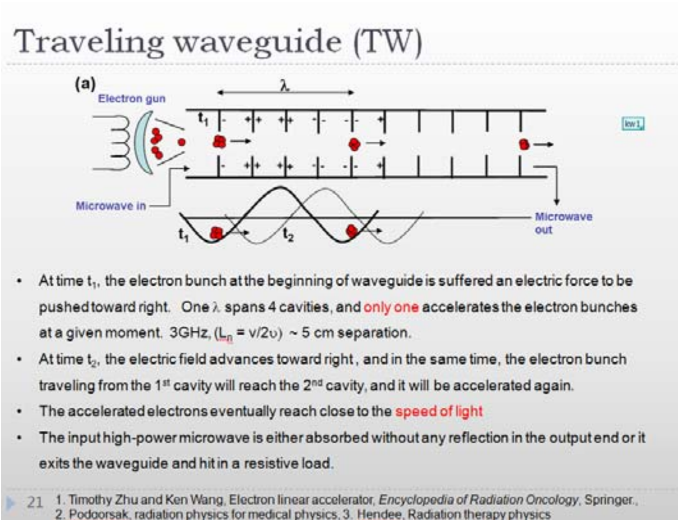
Except rigid mechanical technique determining the stability and accuracy of a waveguide, **conductivity** is another important factor deciding the quality of the waveguides. To achieve the high electrical conductivity at microwave frequencies, the accelerating guide is usually made by copper, resulting in low microwave power loss.

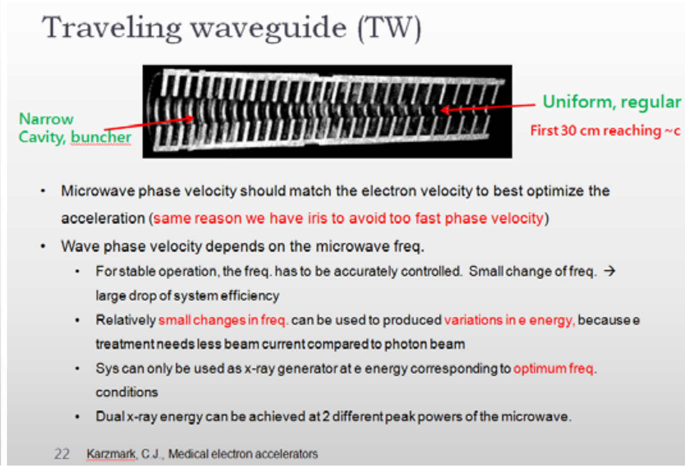
The high vacuum (10^{-6} torr) maintained inside the waveguide is to prevent electron loss and arcing by interacting with air particles [3].

A hollow structure of a waveguide is not suitable for accelerating electrons, because it transmits microwave too fast and the injected electrons are not able to catch up. Hence, the advancing microwave fields are slowed by introducing a series of disks (irises) with hole at the center into the guide. The guide is therefore divided into a series of cavities.

These cavities distribute microwave power between adjacent cavities and produce an appropriate electric field pattern for accelerating electrons.

- Discuss the standing wave and traveling wave accelerating waveguides.





An electron gun sends electrons into the waveguide. The high-power microwave is input by microwave generators into the accelerating waveguide.

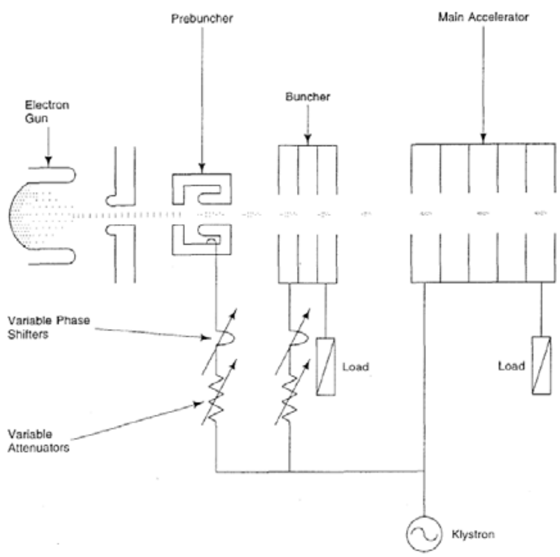


FIGURE 4-8 · (a) A schematic of two section TW linear accelerator.

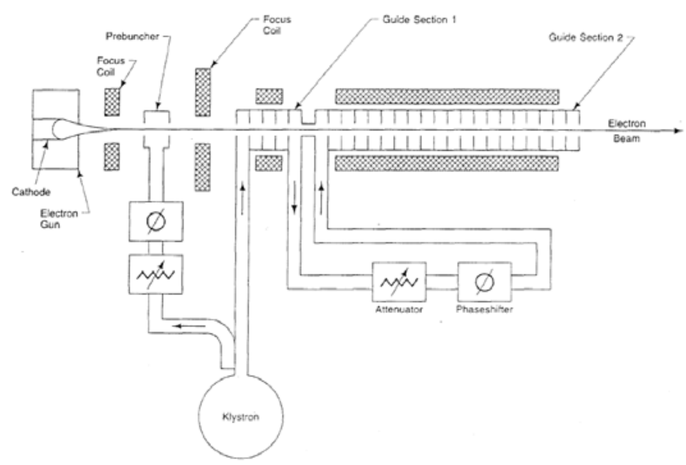


FIGURE 4-8 · (b) A variable energy TW linear accelerator.

- (TW) Picture showing several cavities w/ first several cavities being non-equal spaced and later ones equal spaced. What is this? (Traveling waveguide) Are the cavities equally spaced? (No) Why? In the later cavities, electrons are not gaining speed, are they still gaining energy? How?
- Picture of 4 squares with circle cutouts in the center (to represent traveling waveguide) separated by distances L1, L2, L3 with a plot of a sine wave below. The negative portion of the sine wave was shaded. What is this? Are L1, L2, L3 distances the same? What happens during the shaded portion of the wave? (These wave do not accelerate the energy, and they are just wasted)

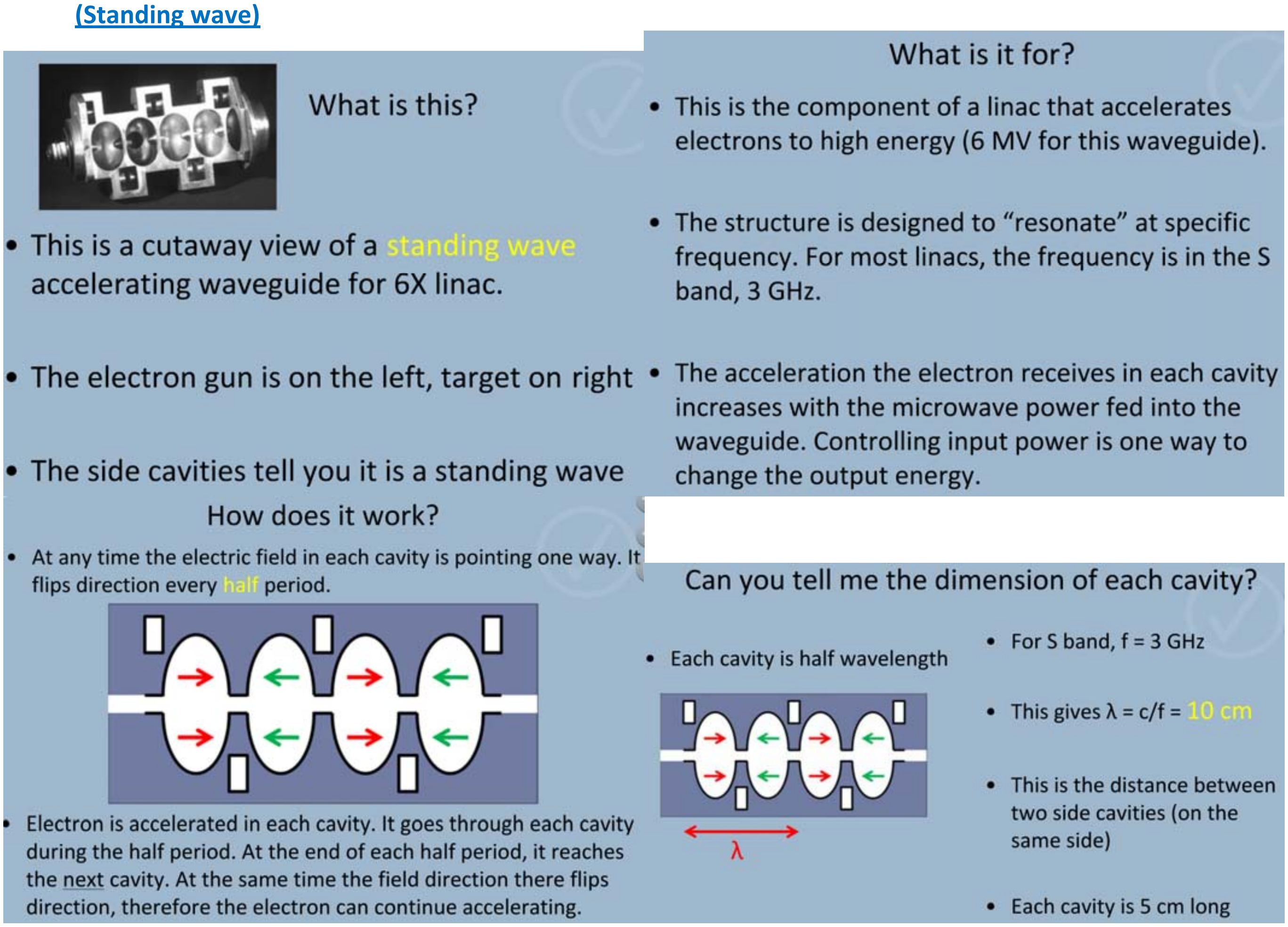
The emitted electrons are formed as "**bunch**" in **buncher** cavity before entering the **main accelerating waveguide**. As the microwave traveling within the guide, it induces an advancing electric field pattern to accelerate the electron bunches.

The functions of the prebuncher and buncher (see Fig. 4-8) are

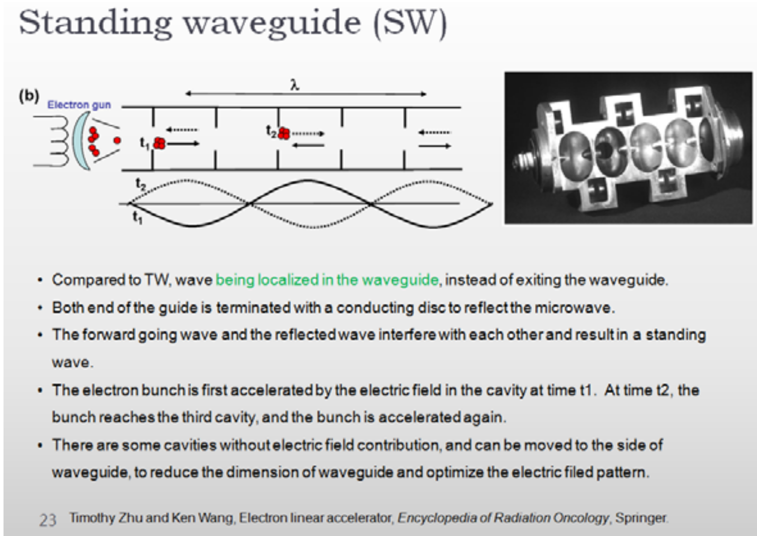
1. To generate, preaccelerate, and shape the electron beam leaving the electron gun.
2. To prebunch electrons with the prebuncher cavity.
3. To accelerate and further bunch the electrons in the buncher so that they match the phase velocity of the rf wave in the main accelerator as they exit the buncher.
4. To tightly bunch the electrons to obtain a narrow electron beam energy spectrum.

The idea of the traveling waveguide is the phase velocity of the E field generated by the microwave needs to match the injected electron velocity so the E field can accelerate the electron in an efficiency way. When the electrons were injected from the gun, they did not travel as a group, and they were with low velocity. The narrow length of bunch is to make the phase velocity of the E field slow enough to accelerate the slow electron in the beginning of the waveguide. After the 1st 30 cm of the TW waveguide, the electron is accelerated "approaching" to light velocity. The bunch width becomes in constant length. However, according to the relativity theory, $E = mc^2/\text{sqrt}(1 - v^2/c^2)$, the particle with mass can't reach light velocity otherwise, we will have infinite energy. Therefore, even the rest of the cavity is in equal length, it still can accelerate electron approaching to the light velocity and increase the electron energy. (The above argument I refer to Karzmark Ch4, the paragraph below eq. (4-32) + my own argument)

(Standing wave)



The 2 cavity for 1 wavelength is already with 2 cavity taken out as side cavity.



The electric field oscillates up and down within the guide but does not propagate. The electron bunch is first accelerated by the electric field (solid line) in the cavity on the left end of the waveguide at time t1.
At time t2, the bunch reaches the third cavity relative to the first one, and the bunch is accelerated again by the standing wave (dash line).

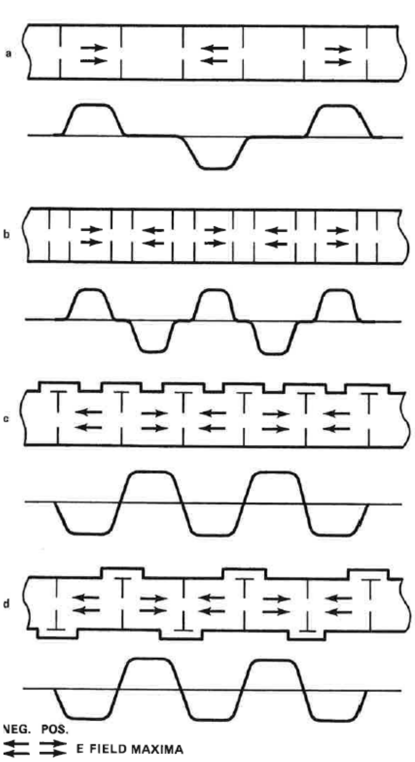


Figure 31. Evolution of side-coupled standing-wave accelerator structure from a linear standing-wave structure and related "E" wave patterns along the axis. The "E" field pattern below each structure shows the spatial field along the axis at the same time in the microwave cycle. The waves are squared due to the presence of harmonics of the fundamental frequency.

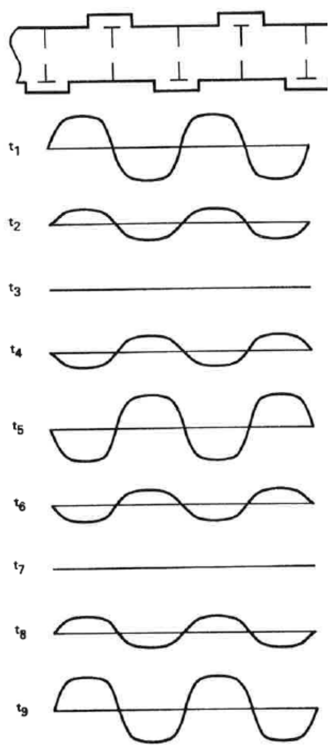


Figure 32. A sequential look at the axial standing-wave "E" field pattern for one full microwave cycle of time for the bimodal structure depicted in Fig. 31d. Note that the "E" field pattern does not advance, but changes in magnitude and direction with time.

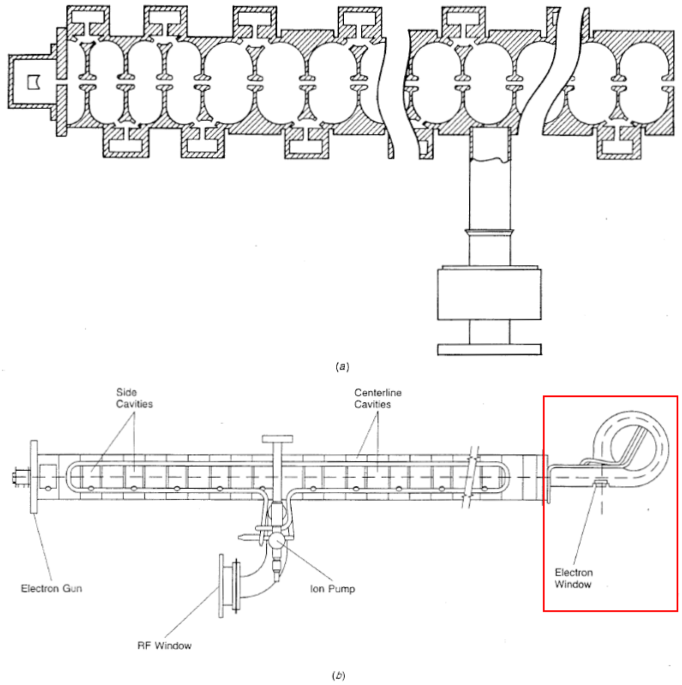


FIGURE 4-26 · Cross-section of typical side-coupled SW linear accelerator structures. (a) A Varian Clinac 20 accelerator and (b) a Siemens Mevatron accelerator.

(Karzmark SW sys, so we can see the electron still goes out from another end)

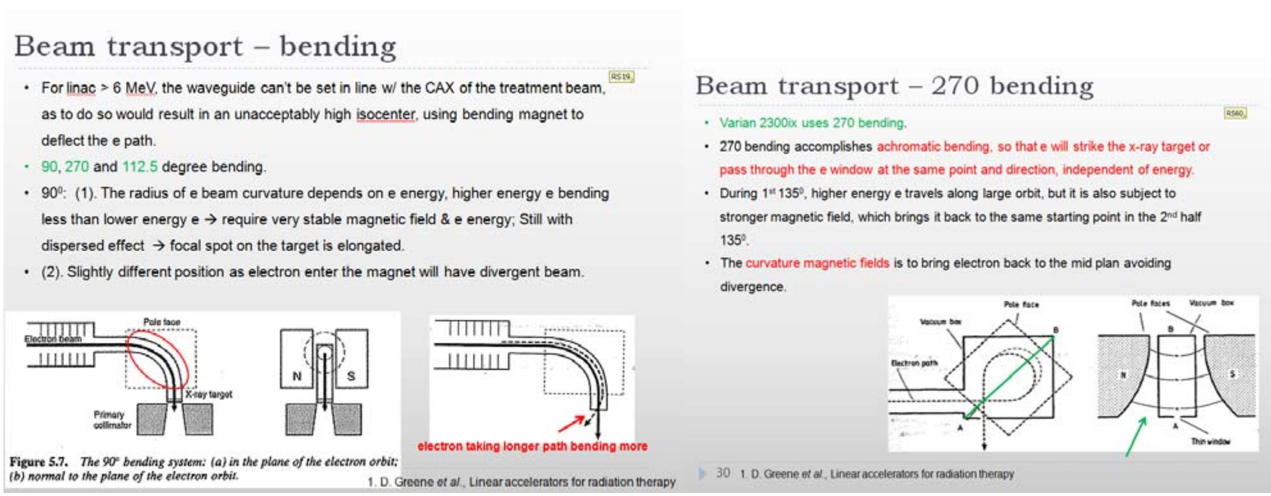
- Discuss the differences between standing wave and traveling wave accelerating waveguides.
    - The essential difference between the traveling and standing waveguide is the wave being localized in the SW, instead of exiting the waveguide.
    - Accelerating gradient is greater for SW (20 MeV/m) than TW (4.3 MeV/m), more energy efficient.
    - TW accelerator for 6X is 1.4 m, compared to SW linac 0.3 m (Karzmark table 4.2)
    - TW systems are easier (less costly) to manufacture because the cavity surfaces need not be as precisely constructed as for SW systems.
    - TW systems are capable of higher electron beam currents.
    - SW is many times more stable in phase vs temperature variations.
    - Ex: Two comparable 6MV accelerators, the TW linac can be powered by 2 MW magnetron but standing wave linac would require a 2.5 MW magnetron. SW needs higher power input to generate the electron with the same energy. Both types of accelerator require similar peak microwave power to achieve the same energy but the mean power is significantly higher for a standing wave accelerator because of the filling time.
    - SW accelerates the electrons in a field of constant amplitude while the field in a travelling wave system is attenuated as it moves along the guide.
    - If the radial dimensions of the accelerator are critical, then the travelling waveguide has the advantage as the side cavities of SW increase the radial dimensions.
    - Waveguide can be 1 - 3m depending on the electron energy required, and it requires a high degree of mechanical rigidity including control of thermal expansion.

An accelerating waveguide - Identify various parts and their function. (vertical orientation, with buncher and catcher cavities, heated cathode)

- - Picture of a resonant cavity. What is a resonant cavity, traveling waveguide?
- (2006) Cartoon picture of a waveguide. Is it SW or TW? where do the e- come from (electron gun)?

- **(Bending magnets)** Shown a diagram of a 90 degree bending magnet with beams coming in straight on, at an angle, and at different angles. Explain why they are deflected onto a target differently. Discuss other types of bending magnets.
- 90 degree magnet (Karzmark's book) Effects of E, position and angular shift. Details about how bending magnet works, 90 vs 270
- (2008) Three images of the accelerated electrons entering the Bending magnet
    - Follow Up:
        - First Image with the electrons bending too quickly
        - Second image with electrons bending slowly or taking a longer curvature
        - Third Image with electrons bending pretty uniformly before hitting the target
        - Explained the Bqv=mv^2/r
        - Asked about the vector in the equation
        - What does the Bending magnet actually do?
        - What is Energy switch (should be slit), Explain?
        - Is the magnet strength same for Low energy and high energy Linac etc.

Bending magnet current AC or DC?



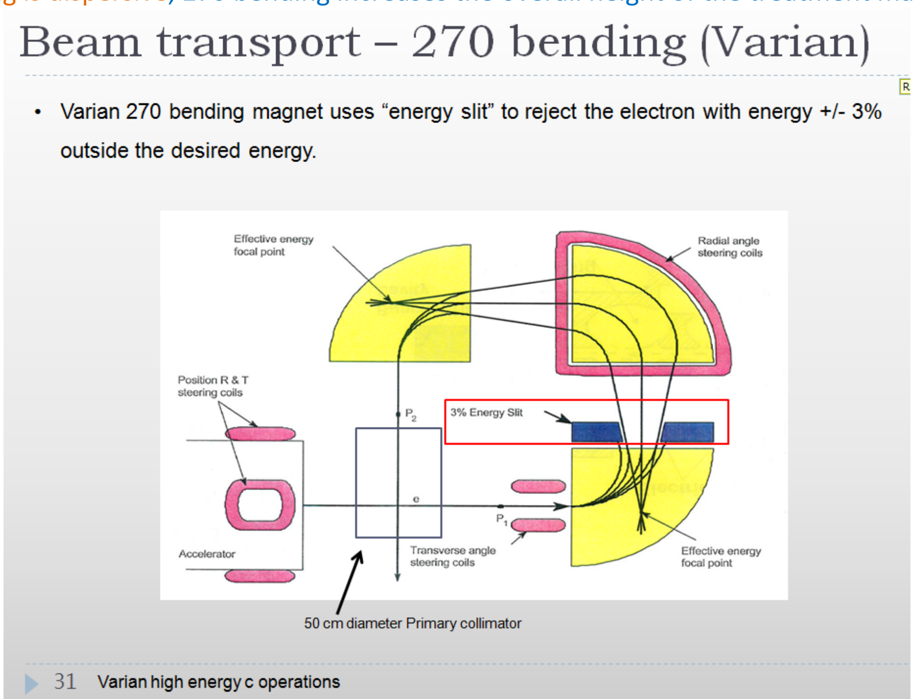
$$F_{centripetal} = F_{magnetic}$$

$$\frac{mv^2}{r} = qvB$$

$$v = \frac{qrB}{m}$$

High energy large velocity, large v → large r (Hendee p66)

Bending radius is proportional to the electron energy, inverse proportional to the bending magnet field strength. For the 90 degree bending, higher energy electrons being bent somewhat less than those of lower energy. Electromagnet is used to allow for the use of different electron energies. The purpose of 270 bending system is to accomplish achromatic bending. More energetic electrons have a larger orbit and will be subject to a stronger field.
The 90 bending is dispersive, 270 bending increases the overall height of the treatment machine.



Most LINACs steer the electron beam using magnetic coils. 2 additional pairs of magnetic coils are placed near the exit of the waveguide. These are called positioning coil (radial & transverse). 2 additional pairs of magnetic coils are placed near the entrance of the waveguide to bend the direction of electron beam radially and transversely. 2 for position (radial & transverse) and 2 for beam angle (radial & transverse). Position controls where the beam hits the target, angle controls the beam direction when it hits the target. You adjust flatness and symmetry by adjusting these steering coils.

An energy selection slit can be inserted between the first and second electromagnets to minimize the spread of electron energies hitting the focal spot. The placement and design of the three magnets is such that after passing through the three magnets, all the electrons will focus on the same spot. The 270 focusing magnet is usually used in the Varian and Siemens accelerators while the 90 focusing magnet is usually used in the Elekta accelerators.

- **(Flattening filter)** in LINAC: Location and what it does. Explain why we can't get rid of the two horns at d_{max}? (use wepassed)

  Between target and ion chamber
  The flattening filter is designed to make flat profile at 10 cm depth. The horn effect we saw in the shallow depth is due to the necessary compromising the flattening filter design. At the deeper depth, due to the flattening filter, we have hardening photon at the central part of the beam, and soft photon close to the field edge entering the water. At the deeper depth, the soft photon is largely absorbed by water, so we can see the flatten profile at the deeper depth. (MetCalf Fig. 4.22)

- **(ion chamber)** Explain where the ion chambers are inside of LINAC. How do they work and how to commission them? When would you know the ion chambers are malfunction? Explain triax cable? Dose monitor chambers in treatment head, - what was it for, how would you check its consistence? what factors affects its operation. Explain physical arrangement in the beam.

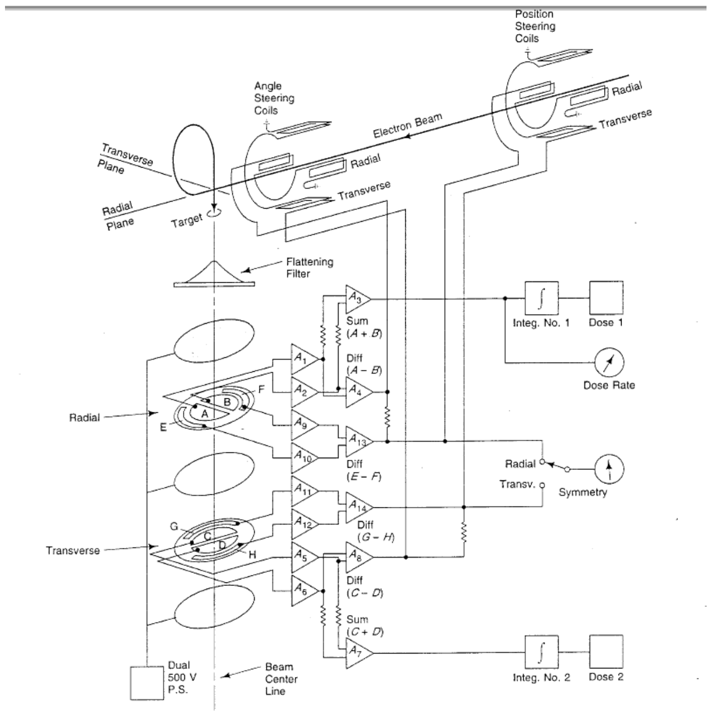
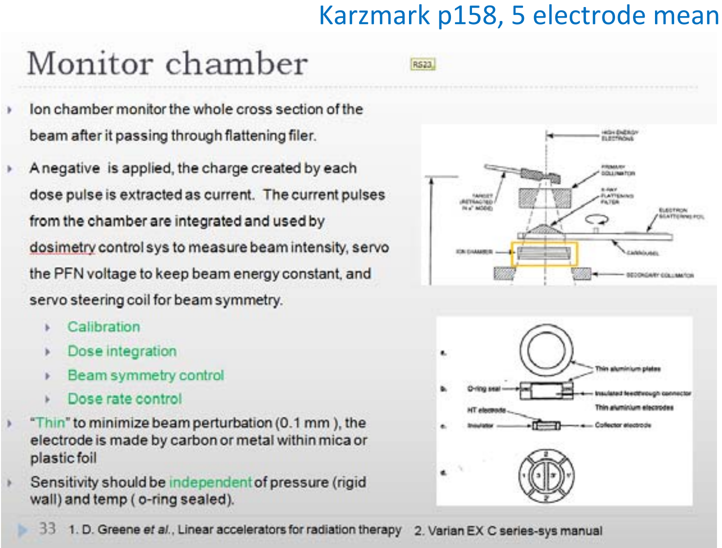
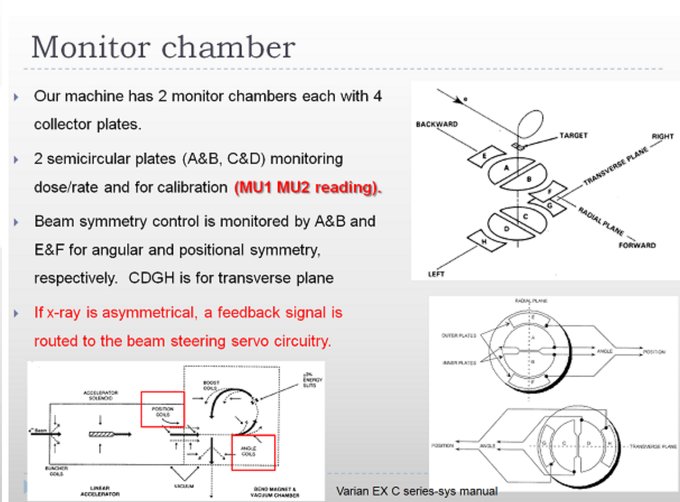


FIGURE 9-1 · Five-electrode ionization chamber with simplified block diagram of dosimetry and beam steering system. The radial and transverse coordinate planes of the bending magnet orbit are identified in the upper left. The radial angle steering coils are actually located in the bending magnet, as shown in more detail in Figure 9-2.

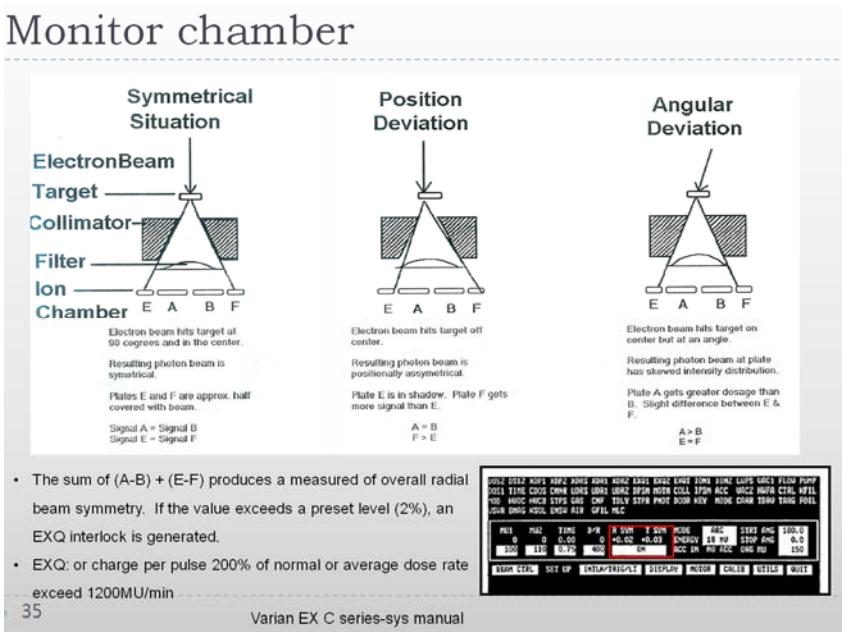
Karzmark p158, 5 electrode meaning 3 polarizing + 2 collecting plate





  - For Varian machine, either for radial or transverse direction, there is for **4** leads of the ion chamber. Using the above figure as an example, AB & CD ionization chamber are used for integration of charge to give dose output (MU1 & MU2) in MU. The A to B & C to D current ratios are compared for feedback to angular beam steering in the radial & transverse plans. The

E to F & G to H current ratios are compared for feedback to the position beam steering in the radial & transverse planes (MetCalf Fig. 1.16(d)).



Monitor chamber is placed below the flattening filter.

- The monitor chamber is often made of multiple layers of parallel plate ionization chambers (0.1 mm thick).
- Within each layer, multiple chambers are used to monitor the beam flatness and symmetry in both the radial and transverse directions.
- For Varian machine, either for radial or transverse direction, there is for **4** leads of the ion chamber. Using the above figure as an example, AB & CD ionization chamber are used for integration of charge to give dose output (MU1 & MU2) in MU. The A to B & C to D current ratios are compared for feedback to angular beam steering in the radial & transverse plans. The E to F & G to H current ratios are compared for feedback to the position beam steering in the radial & transverse planes.
- Primary and secondary monitor chamber readings (MU1 & MU2) are used to determine the dosage (or monitor unit) and will stop the radiation when the appropriate level has been delivered. The level at which a dose difference between MU1 & MU2 triggers termination is equivalent to the 10% of the preset dose or 25 cGy (from IEC 1997 standard).
- Additionally, these chambers act as a safety guard which will turn off the radiation beam if the beam flatness or symmetry drifts out of machine specification.
- In addition, there is a timer which is correlated to the dose rate that will shut off the radiation beam should the monitor chambers fail to do so.

When would you know the ion chambers are malfunction?

MU1 & MU2, Radial and transverse symmetry, dose rate interlock not functions properly.

How to commission monitor chamber?

Check dose/MU linearity, dose rate linearity, dose calibration & profile

how would you check its consistence?
Check the MU linearity, dose rate linearity, & profile.

What factors affects its operation.
3 basic requirements for IC in treatment head are (Green)
(1). It should be thin (0.1mm) so reduce beam perturbation
(2). The sensitivity should be independent of temperature and pressure. If we have a sealed ion chamber, when it has leakage, the chamber reading will change.
(3). It should works at saturation range to avoid ion recombination.

Explain triaxal cable?

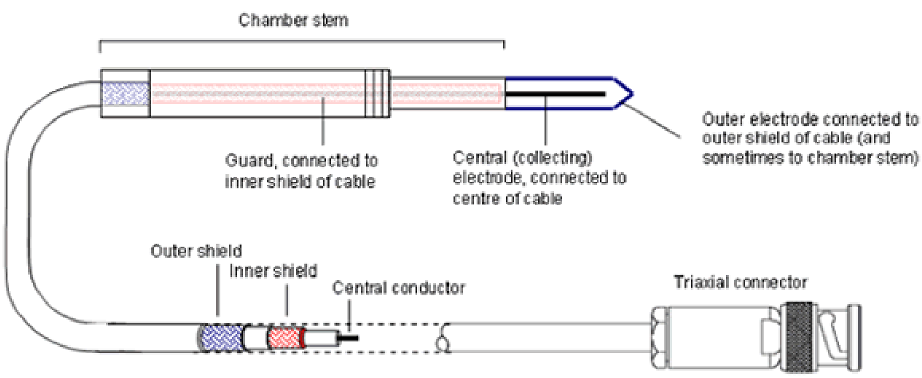
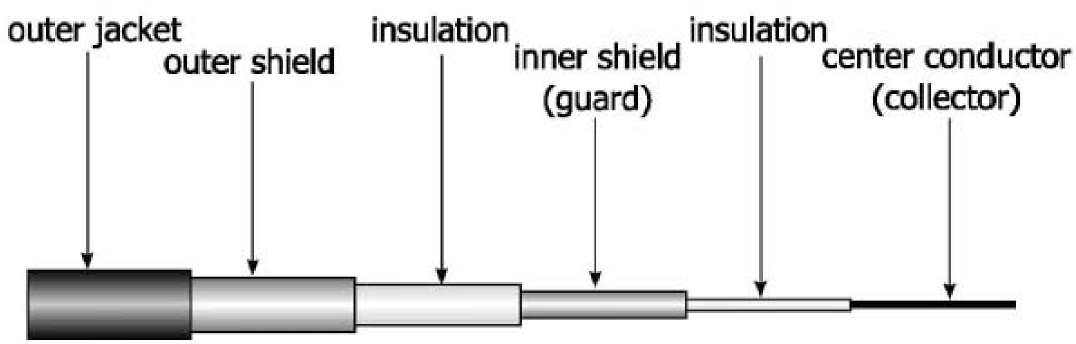


Figure 1: Schematic of a cylindrical ionization chamber showing connections from triaxial cable to chamber electrodes.



'igure 6-8. Schematic of triaxial cable.

(AAPM summer school 2009 Ch6)

A low-noise triaxial cable has insulating qualities that reduce electronic noise from mechanical stress from the cable. The cable should be positioned in a relaxed state, avoiding twisted coils and sharp bends that induce mechanical stress. The guard connector provides a contiguous guard throughout the length of the cable. Connections for the cable have to be secure with good insulation between layers. Also the cleanliness of the connectors is of extreme importance, since one of the major causes of leakage is a dirty connector. Generally, good quality cables and connectors have very low leakage (generally $\leq 10^{-15}$ A, when 300 V is applied). Also desirable for a good triaxial cable is a low capacitance per meter. Cables and ionization chambers should have a fast equilibration time following any change in applied voltage to prevent continually increasing or decreasing readings after a change in voltage.

- **(ion pump)** Discuss the diagram of ion pump. Know to identify it, how it works, what's its use.

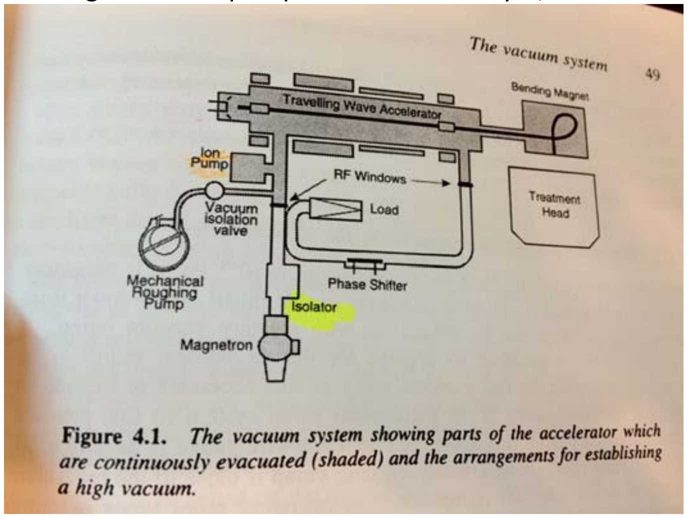
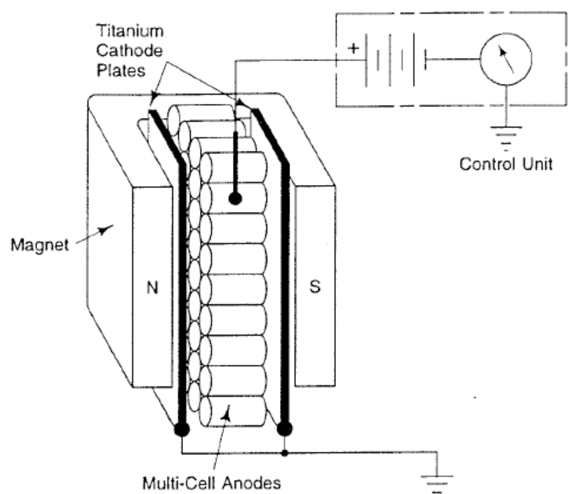


Figure 4.1. *The vacuum system showing parts of the accelerator which are continuously evacuated (shaded) and the arrangements for establishing a high vacuum.*

(Green P.49) The ion pump is used to maintain the pressure of the vacuum system in the linac, because the pressure in linac needs to be as low as 10^{-6} Pa.



Karzmark (p107-108)

To start vacuum the linac system, it starts with "roughing pump" which brings down the pressure from atmospheric pressure to the upper limit of the ion pump 10^-1 pa and then switch to "ion pump" further bringing it down to 10^-6 Pa.

(Hendeep66 + Karzmark107+yy)A sputter-ion pump typically consists of multiple cylindrical anodes positioned between 2 cathodes. The cathodes are sandwiched between the poles of a magnet. The cathodes are composed of a reactive sputtering material such as titanium. Electron ejected from cathodes are attracted toward the anode & assume a spiral path in the magnetic field, and they oscillate between the cathode and collide with gas molecules to produce considerable ionization. The resulting positive ions bombard the cathodes, causing ejection (sputtering) of titanium atom, which are deposited chiefly on the anodes. Freshly sputtered titanium is extremely reactive and will chemically react with active gases. The resulting compounds accumulate on surfaces of the pump elements and pump walls

1. trapping of electrons in orbits by a magnetic fields
2. ionization of gas by collision with e-
3. sputtering of titanium by ion bombardment
4. chemical reaction between active gases and titanium

(Arthur) Ion Pump is not a monitor, it is a pump, it removes impurities from the accelerating guide system. Ion pumps have specific lifetime as the impurities get trapped in the ion pump and eventually the active material will get saturated, so efficiency of pumping out ions out of the system decreased with time

(Green p49)The gas discharge current within the pump can be used as a pressure indicator, which is dependent on the gas pressure, and the amount of the current can be calibrated as a pressure gauge. A control signal proportional to the current can be used within other parts of the linac control circuitry to provide interlocks which prevents operation of the modulator & the e gun filament supply if the pressure rises above a predetermined value. The working range of ion pump is $10^{-1} – 10^{-6}$ Pa.

- (QA): Picture of Linac head shown with parts – waveguide, bending magnet, flattening filter, scattering foil, monitor chambers, jaws & MLCs. What annual test checks the proper functioning of each of these parts?

  Waveguide: PDD, energy verification, flatness and symmetry, dose calibration
  Bending magnet: PDD, energy verification, flatness and symmetry, dose calibration
  Flattening filter: PDD, flatness and symmetry, dose calibration
  Scattering foil: PDD, flatness and symmetry, dose calibration
  Monitor chambers: dose/MU linearity, dose rate linearity, dose calibration, profile
  Jaws: light-to-rad test, independent jaw calibration (position) test …
  MLCs: MLC collimator radiation star, picket fence test, leaf position check with light field, leaf position reproducibility…

Machine	Component	NAP	% DD	Profiles	Dose calibration
In-line	magnetron	X		X	X
	Ion chamber			X	X
	Tgt/gun/guide	X	X	X	X
With magnet	Klystron/magnetron	X			X
	Gun	X			X
	Ion chamber			X	X
	Foil/flat. Filter		X	X	X
	Guide	X	X	X	X
	Bending magnet	X	X	X	X

(what need to be checked when we change these components)

(Linac vs. conventional simulator) Picture of a Linac. Name the components. What's the difference between this and a conventional simulator? FU: What about the jaws? FU: More discussion of the components of the linac

Identify components on an accelerator and state what components are also on a conventional simulator (collimator, gantry, couch, wire simulated jaw position, Varian acuity has DSP for MLC & CBCT)

Identify components on an accelerator and how to QA them (collimators, filter, target, beam magnet)

What's the difference between a linac and a conventional simulator? (we passed + MetCalf p394)
The main difference is that the simulator only has diagnostic (kV) source 120 kVp, 40 keV instead of the MV source in the actual linac.

Varian acuity does not have linac kind of jaw but it equipped with mobile wire. With the light projection, it can simulate the jaw position. Varian acuity also has the digital shape projector (DSP) used to project optically generated complex shapes, MLC overlays or delineating the wire asymmetrical/symmetrical fields onto a patient during simulation.

The main advantage for classical simulation technique:
(a). A target area is clearly defined in BEV in relation to sensitive structures within & beyond the treatment field margins.
(b). Treatment machine parameters such as gantry, collimator, & couch angle, as well as jaw sizes can be preset for use in calculations by the TPS & ultimately used in linac
(c). Treatment strategy can be devised prior to placement of pt. on the linac, thus minimizing setup time on the linac.

(Wepassed) It does have light field so you can setup the patient in the same way you setup the patient at the treatment table. Also the simulator room has room laser similar to the linac vault. A simulator can reproduce the range of motion of the gantry, table, and collimator. A simulator does not have MLC but you can take a port film with the simulator and the radonc will draw block on it (to be treated with actual block or MLC). (Varian acuity has DSP to mimic the MLC). Most places have gotten rid of their conventional simulator. They replace it with virtual CT-based simulation.

- Discuss a cross-section of a betatron. What dose does it produce? How does it work? Compare with Linacs, how is a beam produced?

(Kahn 4.4)

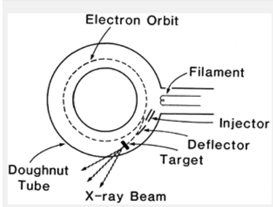


FIG. 4.10. Diagram illustrating the operation of a betatron.

The operation of the betatron is based on the principle that an electron in a changing magnetic field experiences acceleration in a circular orbit. The accelerating tube is shaped like a hollow doughnut and is placed between the poles of an alternating current magnet. A pulse of electrons is introduced into this evacuated doughnut by an injector at the instant that the alternating current cycle begins. As the magnetic field rises, the electrons experience acceleration continuously and spin with increasing velocity around the tube. By the end of the first quarter cycle of the alternating magnetic field, the electrons have made several thousand revolutions and achieved maximum energy. At this instant or earlier, depending on the energy desired, the electrons are made to spiral out of the orbit by an additional attractive force. The high-energy electrons then strike a target to produce x-rays or a scattering foil to produce a broad beam of electrons.

Moreover, many radiation therapists regard the small field size and low x-ray dose rate of the betatron as serious disadvantages to the general use of the device, compared to linac.

C5-C (Diagnostic x-ray)

- Shown a picture of a diagnostic x-ray tube. Identify various parts? What are apparent and effective focal spots? Typical target angles? Why is focal spot size so important? What are the electronics associated with the x-ray production?
- What are examples of target materials, what is the process of x-ray productions, why is the target angled? What is the wall material of the tube and why?
- Picture of basic x-ray tube. What type of electronics/circuits is used (supposed to say step-up transformer and voltage rectifier).

(Kahn Ch3.1 – 3.3)

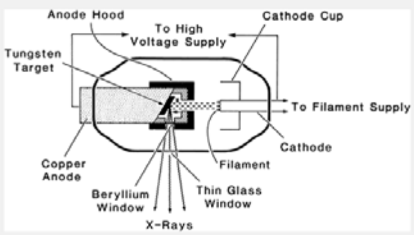
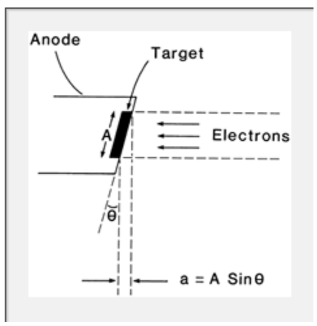


FIG. 3.1. Schematic diagram of a therapy x-ray tube with hooded anode.



a: apparent focal spot

Figure 3.1: The tube consists of a glass envelope which has been evacuated to high vacuum. At one end is a cathode (negative electrode) and at the other an anode (positive electrode). The cathode is a tungsten filament which when heated emits electrons, a phenomenon known as thermionic emission. The anode consists of a thick copper rod at the end of which is placed a small piece of tungsten target. When a high voltage is applied between the anode and the cathode, the electrons emitted from the filament are accelerated toward the anode and achieve high velocities before striking the target. The x-rays are produced by the sudden deflection or acceleration of the electron caused by the attractive force of the tungsten nucleus (Bremsstrahlung production). The x-ray beam emerges through a thin glass window in the tube envelope. In some tubes, thin beryllium windows are used to reduce inherent filtration of the x-ray beam.

Target in Anode:

Tungsten (z = 74) as the target material (1). high atomic number (high efficiency of x –ray generation) and (2). high melting point (3370 degree for Tyngsten) to withstand intense heat produced in the target by the electronic bombardment.

Efficient removal of heat from the target is an important requirement for the anode design.

(1). This has been achieved in some tubes by conduction of heat through a thick copper anode to the outside of the tube where it is cooled by oil, water, or air.

(2). Rotating anodes have also been used in diagnostic x-rays to reduce the temperature of the target at any one spot. The heat generated in the rotating anode is radiated to the oil reservoir surrounding the tube.

It should be mentioned that the function of the oil bath surrounding an x-ray tube is to insulate the tube housing from high voltage applied to the tube as well as absorb heat from the anode.

(Focal spot) An important requirement of the anode design is the optimum size of the target area from which the x-rays are emitted. This area, which is called the focal spot, should be as small as possible for producing sharp radiographic images. However, smaller focal spots generate more heat per unit area of target and, therefore, limit currents and exposure.

(Apparent focal spot & angle) The apparent size of the focal spot can be reduced by the principle of line focus, illustrated in Fig. 3.2. The target is mounted on a steeply inclined surface of the anode. The apparent side a is equal to A $\sin\theta$, where A is the side of the actual focal spot at an angle θ with respect to the electron beam. Since the other side of the actual focal spot is perpendicular to the electron, its apparent length remains the same as the original. The dimensions of the actual focal spot are chosen so that the apparent focal spot results in an approximate square. Therefore, by making the target angle θ small, side a can be reduced to a desired size. In **diagnostic radiology**, the target angles are quite small (**6-17 degrees**) to produce apparent focal spot sizes ranging from **0.1 x 0.1 to 2 x 2 mm**. In most **therapy tubes (such as superficial x-ray)**, however, the target angle is larger (about 30 degrees) and the apparent focal spot ranges between 5 x 5 to 7 x 7 mm.

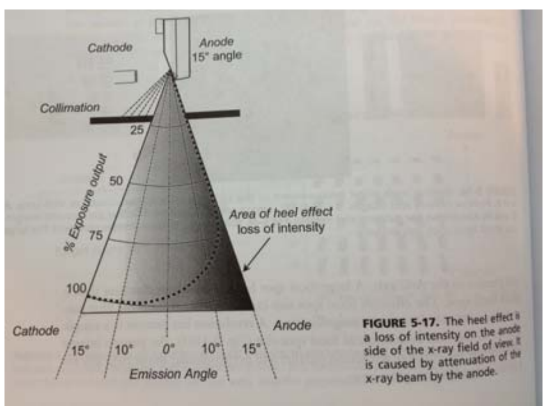


FIGURE 5-17. The heel effect is a loss of intensity on the anode side of the x-ray field of view. It is caused by attenuation of the x-ray beam by the anode.

(heel effect) Since the x-rays are produced at various depths in the target, they suffer varying amounts of attenuation in the target. Consequently, the intensity of the x-ray beam decreases from the cathode to the anode direction of the beam. This variation across the x-ray beam is called the heel effect. The effect is particularly pronounced in diagnostic tubes because of the low x-ray energy and steep target angles. The problem can be minimized by using a compensating filter to provide differential attenuation across the beam in order to compensate for the heel effect and improve the uniformity of the beam.

The **cathode** assembly in a modern x-ray tube (Coolidge tube) consists of a wire filament, a circuit to provide filament current, and a negatively charged focusing cup. The function of the cathode cup is to direct the electrons toward the anode so that they strike the target in a well-defined area, the focal spot. Since size of focal spot depends on filament size, the diagnostic tubes usually have two separate filaments to provide "dual-focus", namely one small and one large focal spot. The material of the filament is tungsten, which is chosen because of its high melting point.

- What type of electronics/circuits is used (supposed to say step-up transformer and voltage rectifier).

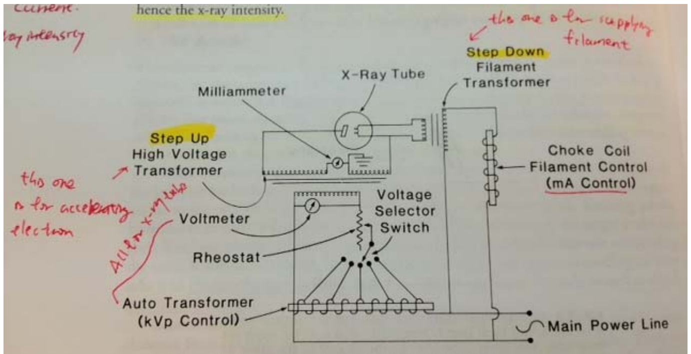


FIG. 3.3. Simplified circuit diagram of a self-rectified x-ray unit.

A simplified diagram of a self-rectified therapy unit is shown in Fig. 3.3. The circuit can be divided into 2 parts: (1). the high-voltage circuit to provide the accelerating potential for the electrons and (2) the low-voltage circuit to supply heating current to the filament. Since the voltage applied between the cathode and the anode is high enough to accelerate all the electrons across to the target, the filament temperature or filament current controls the tube current (the current in the circuit due to the flow of electrons across the tube) and hence the x-ray intensity.

(Step-down filament transformer) The filament supply for electron emission usually consists of **10 V** at about 6 A. As shown in Fig. 3.3, this can be accomplished by using a step-down transformer in the AC line voltage. The filament current can be adjusted by varying the voltage applied to the filament.

(Step-up HV transformer) The high voltage to the x-ray tube is supplied by the step-up transformer (Fig. 3.3). The primary of this transformer is connected to an autotransformer and a rheostat . The function of the autotransformer is to provide a stepwise adjustment in voltage. The device consists of a coil of wire wound on an iron core and operates on the principle of inductance. When an alternating line voltage is applied to the coil, potential is divided between the turns of the coil. By using a selector switch, a contact can be made to any turn, thus varying the output voltage which is measured between the first turn of the coil and the selector contact.

Voltage rectification

The **disadvantage** of the self-rectified circuit is that no x-rays are generated during the inverse voltage cycle (when the anode is negative relative to the cathode), and therefore, (1). the output of the machine is relatively low. Another problem arises when the **target** gets hot and emits electrons by the process of thermionic emission. During the inverse voltage cycle, these electrons will flow from the anode to the cathode and bombard the cathode filament. This can destroy the filament.

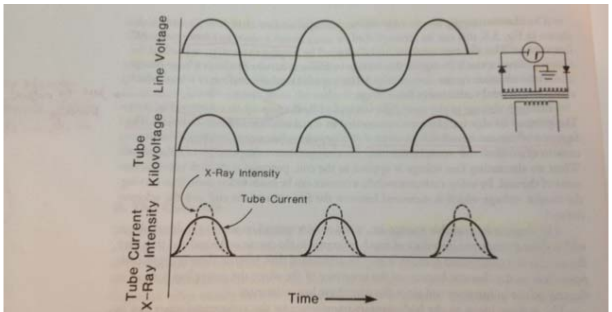


FIG. 3.4. Graphs illustrating the variation with time of the line voltage, the tube kilovoltage, the tube current, and the x-ray intensity for self- or half-wave rectification. The half-wave rectifier circuit is shown on the right. Rectifier indicates the direction of conventional current (opposite to the flow of electrons).

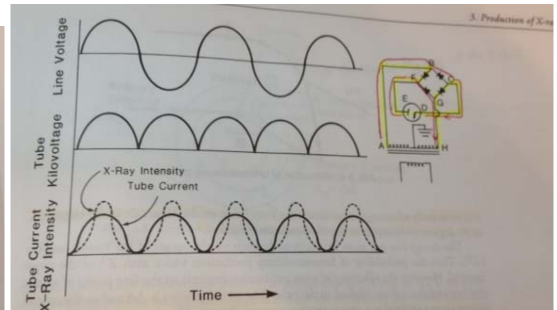


FIG. 3.5. Graphs illustrating the variation with time of the line voltage, the tube kilovoltage, the tube current, and the x-ray intensity for full-wave rectification. The rectifier circuit is shown on the right. The arrow symbol on the rectifier diagram indicates the direction of conventional current flow (opposite to the flow of electronic current).

The problem of tube conduction during inverse voltage can be solved by using voltage rectifiers. Rectifiers placed in series in the high-voltage part of the circuit prevent the tube from conducting during the inverse voltage cycle. The current will flow as usual during the cycle when the anode is positive relative to the cathode. This type of rectification is called half-wave rectification and is illustrated in Fig. 3.4.

Rectifiers can also be used to provide full-wave rectification. As a result of full-wave rectification, the effective tube current is higher since the current flows during both half-cycles.