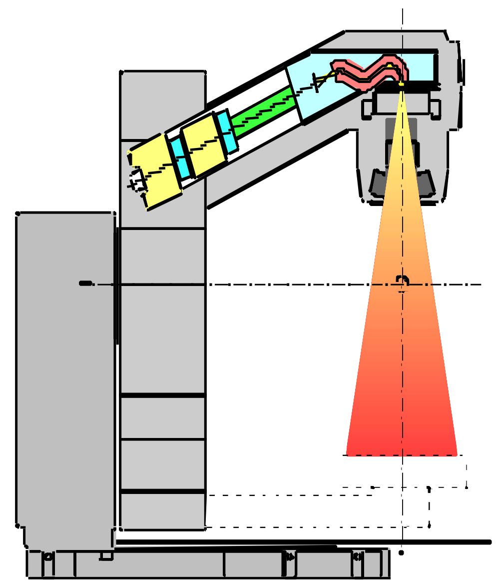
Therapy Electron Linear Accelerators

Explained

Accelerator Building Blocks

- Power source
- Electron source
- Accelerator structure
- Beam bending system
- Beam Conditioning
- Collimation system
- Control system
- Support structure



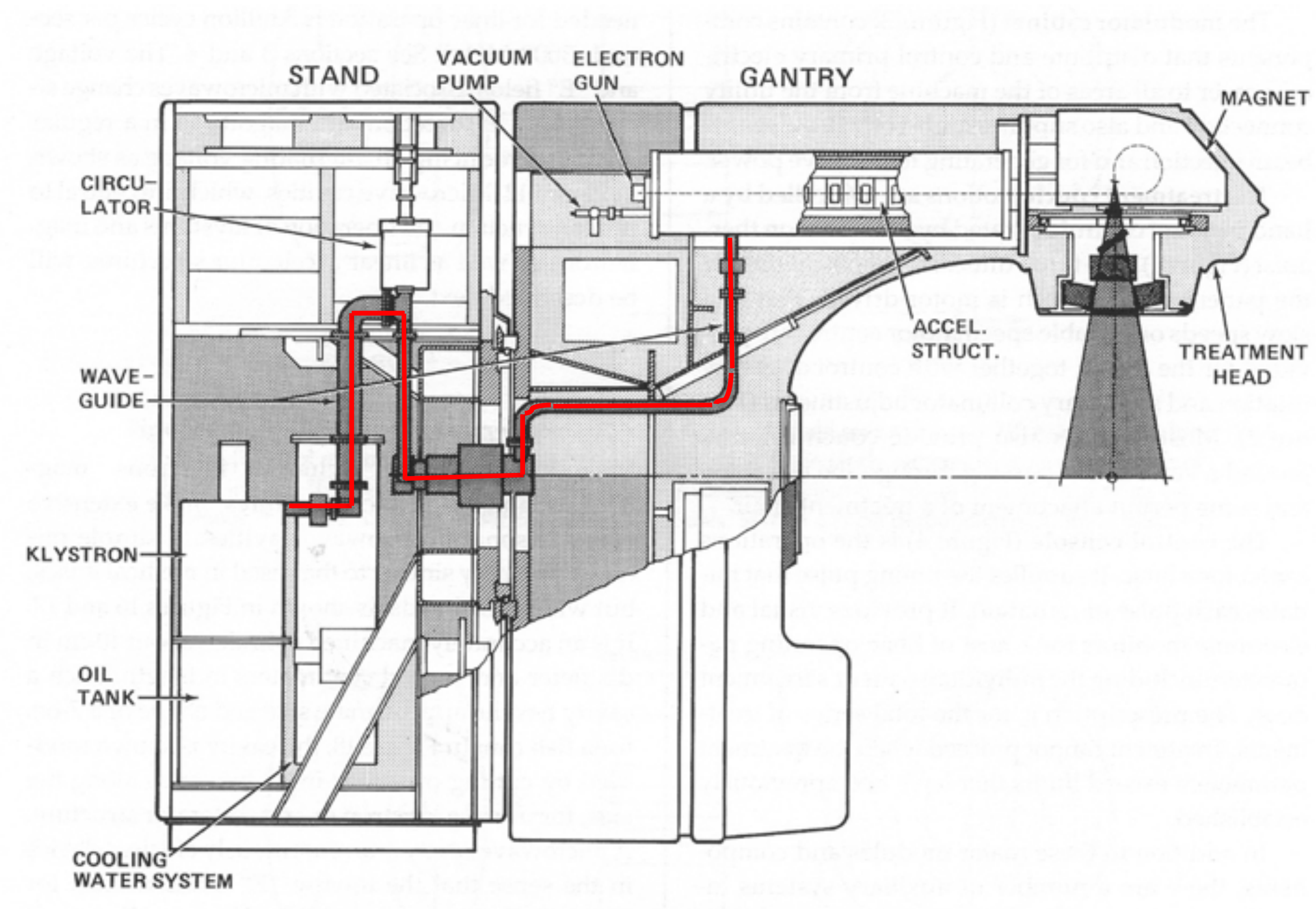
Waveguide

- Conveys microwave power to accelerator guide
- System of hollow pipes
  - Rectangular or circular in cross section
- Replace traditional electrical wires / cables
  - Inefficient in transmitting power at microwave frequencies

Waveguide

- Confine microwaves by reflecting them forward off the walls of the guide
    - Like a hose pipe confines water flowing through it
- Pressurised with an insulating gas
    - – Reduces possibility of electrical breakdown
        - i.e. increases power handling capability
        - SF6 (0.7 – 2.1 bar)
- Two ceramic windows separate waveguide from
    - Evacuated power source
    - Evacuated accelerator guide
- Windows transparent to microwaves

Waveguide


STAND
VACUUM PUMP
ELECTRON GUN
GANTRY
MAGNET
CIRCU-LATOR
ACCEL. STRUCT.
TREATMENT HEAD
WAVE-GUIDE
KLYSTRON
OIL TANK
COOLING WATER SYSTEM

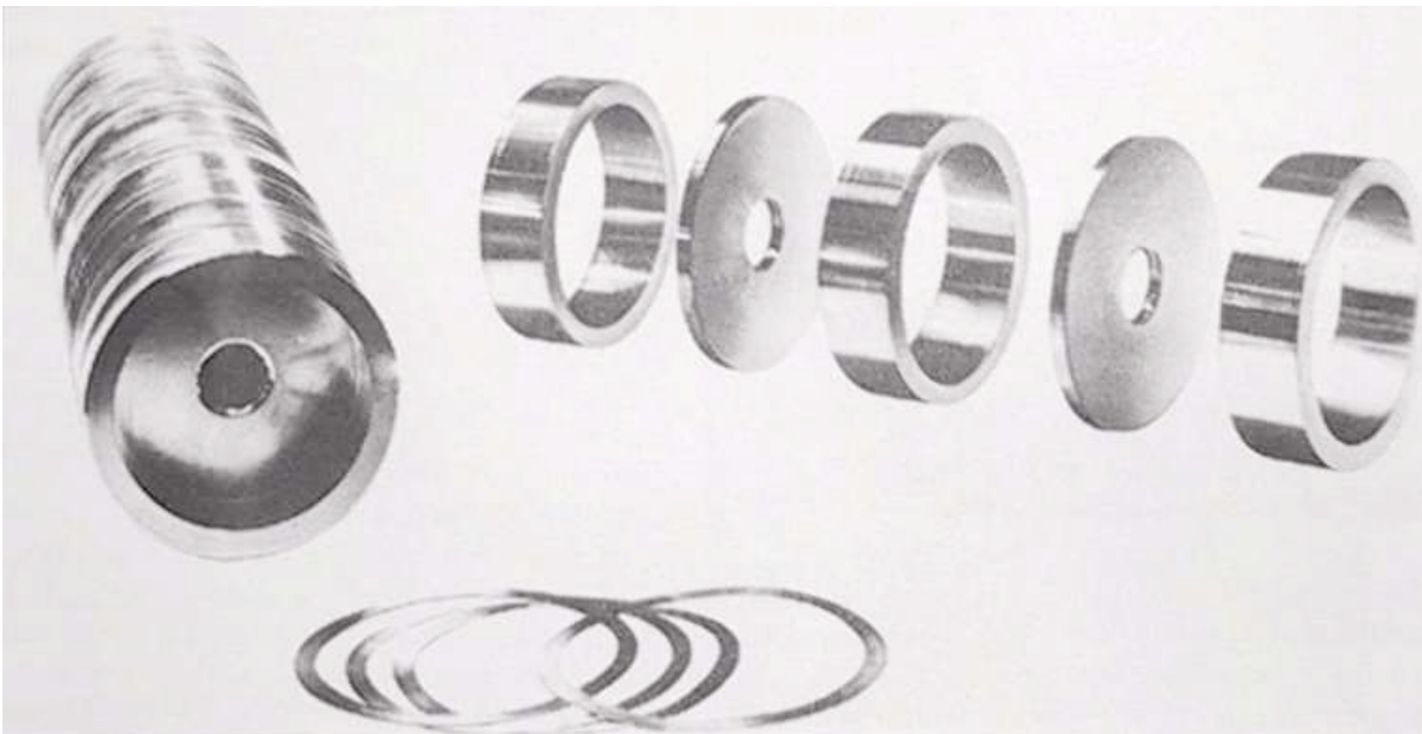
Goals of Accelerator Structure

- High capture of injected electrons
- Maintain narrow energy definition
- Operate over a range of energies
- Stable - low and high current capability
- Low stray leakage radiation

Accelerator Structure

- Long series of microwave cavities
  - Adjacent, cylindrical & evacuated
  - Located in the rotating gantry
  - Overall structure varies in length
    - 30 cm for 4 MeV
    - > 1 m for high-energy units
- Objective is energy transfer
  - From cavity "E" fields
  - To an accelerating **e**$^-$beam

Accelerator Structure



From: "A Primer on Theory and Operation of Linear Accelerators in Radiation Therapy" by C. J. Karzmark, Robert J. Morton

- Basic Element of linac
  - Accelerator structure (waveguide)
  - Looks like a length of hollow copper pipe
  - Divided into sequence of microwave cavities
    - Series of washer like disks
  - rf waves guided along the length of the pipe
    - Produces an alternating electric force on electrons on its axis
  - rf waves pulsed into the pipe from a microwave power source
    - Magnetron or Klystron

  - Electrons emitted from a hot cathode in an electron gun
    - Accelerated through a hole in an anode
      - Into the pipe in pulses
      - by switching a kV pulse to the gun
      - => Pencil beam of electrons injected into pipe

- Electrons then formed into bunches a few cm apart in the pipe
    - And ride (surf) the electromagnetic wave down the pipe

- The rf power fed into the pipe causes current to flow on the inner cavity surfaces
  - setting up an alternating electric field along the cavity axes
  - The axial electric field in each cavity of the structure oscillates at 3 GHz
    - This oscillation in each successive cavity is delayed (phased) w.r.t. the previous cavity
    - When electron bunch arrives at each cavity it is further accelerated

Accelerator Structure

- 1st few cavities vary in size
    - Accelerate & Bunch
- Typically 33% injected electrons captured
- Electrons gain energy and increase speed until they reach relativistic velocity
    - "almost the speed of light"
    - Happens in first few cavities
        - ~ first 30 cm of waveguide

Accelerator Structure

- First few cavities designed
  - to propagate "E" field with increasing velocity in order to
    - bunch & further bunch electrons
    - accelerate bunches to relativistic velocity
- First few cavity dimensions differ
  - Larger and variable aperture sizes
  - Shorter and variable lengths

Accelerator Structure

- Later cavities
  - Uniform in size
  - Provide constant velocity wave
    - At or close to speed of light
- Electrons gain energy
  - Initially & predominantly by increasing their velocity
  - Later by increasing their relativistic mass
    - e.g. 2 MeV e^- moves at 0.979c

      its mass in motion is ~ 5times its mass at rest

	Energy	Relative Velocity
Buncher Section	10keV	0.197
	15keV	0.242
	1MeV	0.942
	2MeV	0.979
Main Section	3MeV	0.989
	4MeV	0.993
	5MeV	0.995
	6MeV	0.9969
	10MeV	0.998
	15MeV	0.99945
	18MeV	0.9996
	20MeV	0.99968
	21MeV	0.99971
	25MeV	0.99979
Info only	100MeV	0.99998
	1000MeV	0.9999998

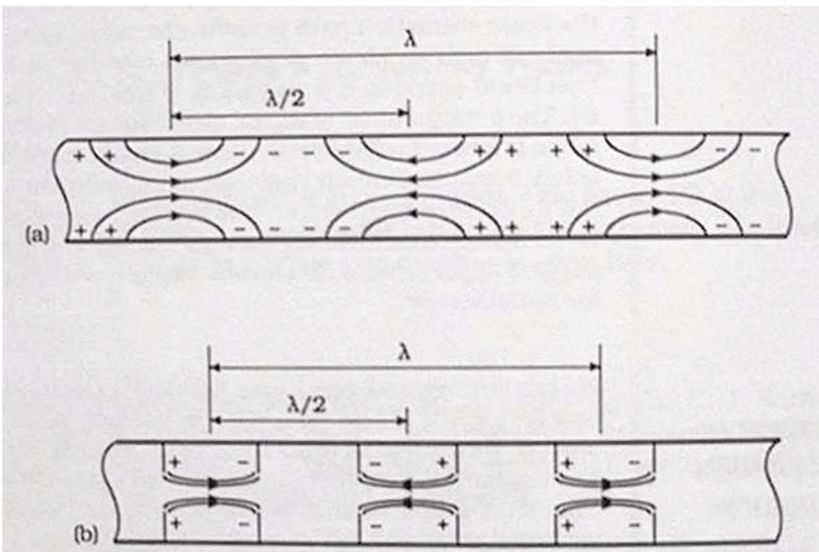
Accelerator Structure

- Two types of accelerator structures
  - Travelling-wave
  - Standing-wave
- The "E" field patterns behave differently
  - Central to understanding concept of linacs

Travelling-Wave Accelerator

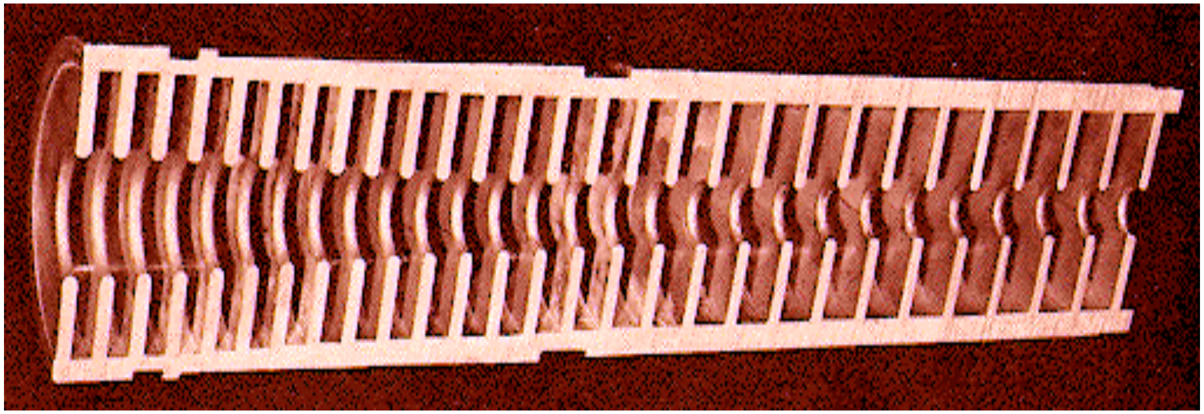
- Microwaves travel at *c* the speed of light in free space
- Velocity of propagation in a waveguide depends on
  - Wavelength
  - Dimensions & shape of guide

Travelling-Wave Accelerator



- Direction of "E" field reversed every half wavelength
- Pattern repeats every wavelength
- There are 4 cavities per wavelength

Electron Capture and Bunching

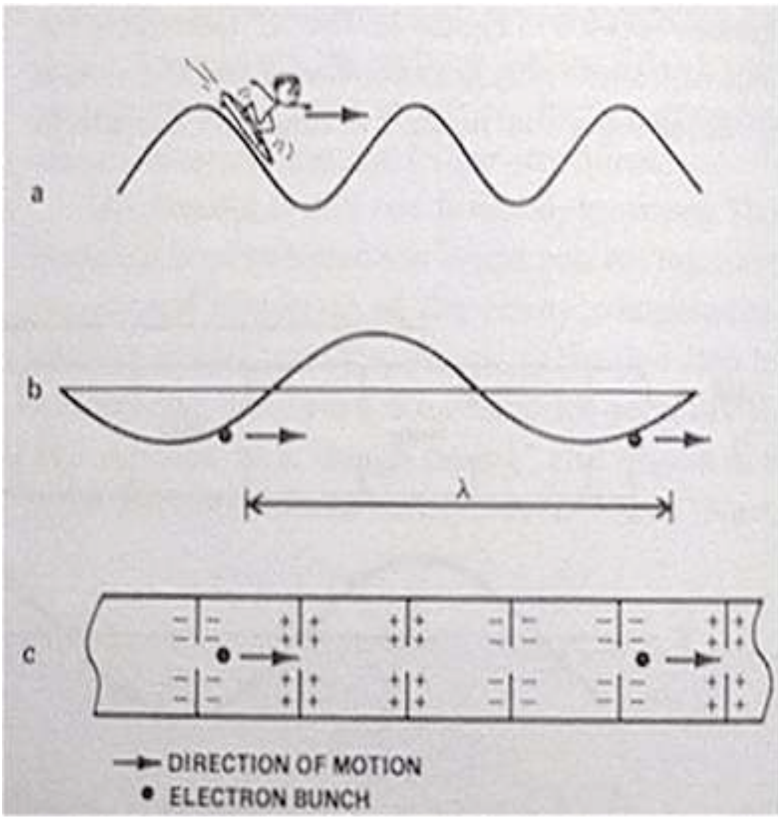


Cut-away of an early prototype travelling-wave accelerator structure

Tapered bunching section on the left

Continued energy gain with uniform section on right

Electron Capture & Bunching



a) Travelling-wave analogy

b) Electron bunch on an advancing (negative) electric "E" field

c) Associated charge distribution that pushes (-) and pulls (+) electron bunches along the cylinder

Standing-Wave Accelerator

- Operate somewhat like travelling-wave units
- One significant difference
- "E" wave varies in magnitude with time in a sinusoidal manner
- But pattern remains stationary along axis
  - Does not advance like travelling "E" wave
    - Or water wave analogy
- An analogy for the E field:
    - Pattern of a violin string fixed at both ends and vibrating up and down to produce a musical note

Standing-Wave Accelerator

- In the standing-wave accelerator, at both ends of the accelerator structure the rf power is reflected back and forth to create a standing wave within the accelerator.
- The resulting standing-waves are spatially stationary in phase, but their magnitude oscillates in time.
- In order to accelerate e's efficiently with these standing-waves, the length of each cavity should be chosen to be equal to one-quarter wavelength.
- Half of the cavities have zero field at all times, and thus have no role in acceleration, these cavities can be very short or moved off the beam axis. This shortens the overall structure length considerably

Standing-Wave Accelerator

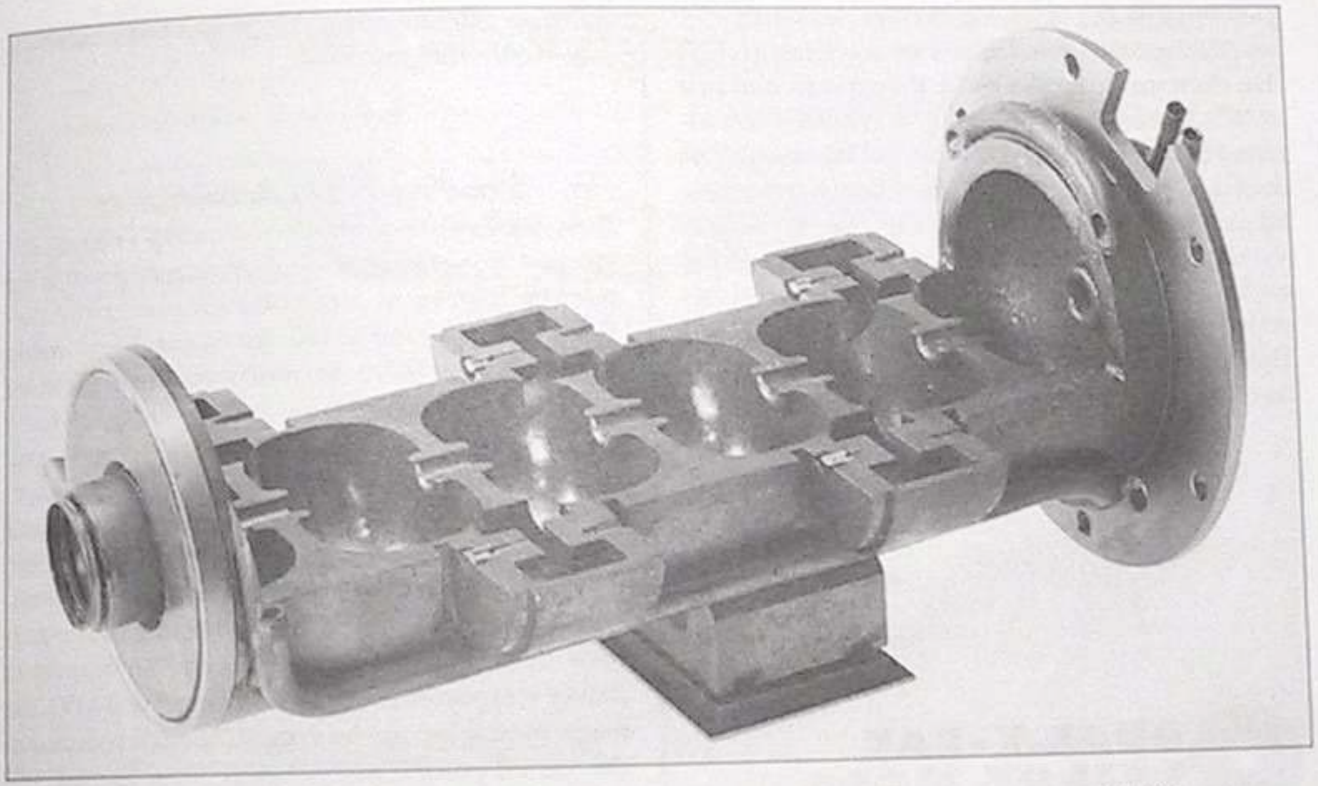
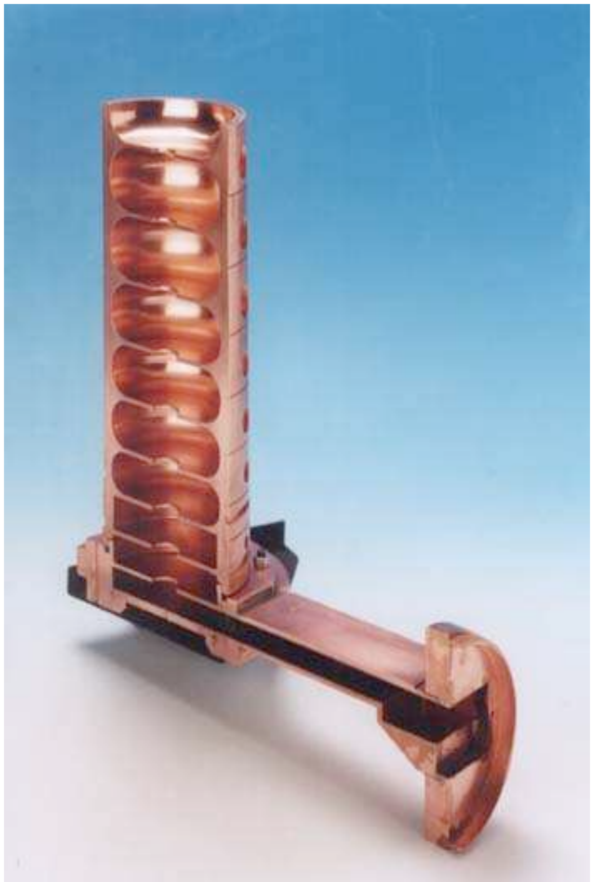


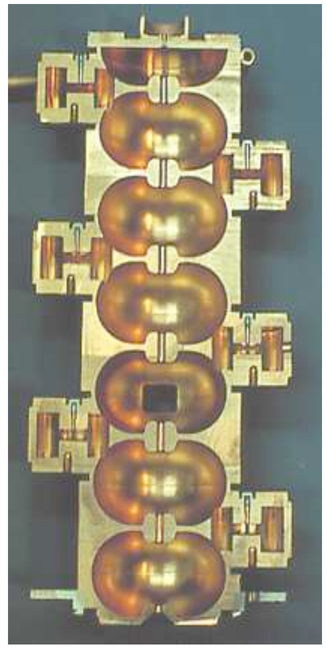
Figure 34. Cutaway view of a standing-wave linac structure. Electrons attain an energy of 4 MeV in this 30 cm long structure with five accelerating cavities. The input waveguide is on the bottom, the electron gun attaches on the left, and the x-ray target is permanently sealed into the structure on the right end. (Clinac 4, courtesy of Varian Associates.)

From: “A Primer on Theory and Operation of Linear A ccelerators in Radiation Therapy” by C. J. Karzmark, Robert J. Mo rton

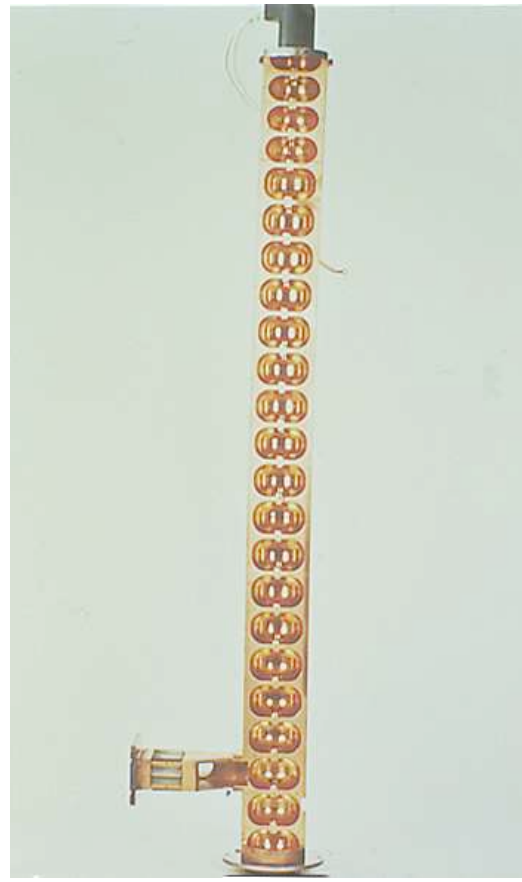
Accelerator Structures



Short section - TW accelerator



Short section
SW accelerator



Long section - SW accelerator

Dual X-ray Energy Accelerators

- Two or more x-ray photon modes
  - e.g. 6/10 **MV** or 6/15 **MV** photons
- Range of electron energies
  - e.g. 6,9,12,15, 18 & 21 **MeV** electrons
- Require to produce high and low energy photons at an adequate dose rate
  - Lower photon energies require higher beam current
    - X-ray production efficiency markedly reduced at low energy
    - => dose rate reduced
  - All electron energies require much smaller beam currents
- The travelling-wave linac is used for lower up to medium energies, standing-wave linacs are used for energies above 8-10 MeV.

The Treatment Head

- For radiotherapy applications, the beam must obey certain specifications. It must have
  - A narrow energy specification
  - Be homogenous
  - Symmetric
- After exiting the waveguide, the beam does not have these properties, control and focusing are required.
- The treatment head is that part of the machine which receives the high energy electrons from the accelerating structure. In the head, an electron or X-ray beam is generated which can be used for treating patients.
- The treatment head can be either in line with the accelerating waveguide or at right angles, in which case a beam bending magnet is required. Medical linacs with higher energies are commonly equipped with bending magnets, as otherwise the height of the gantry becomes too large.

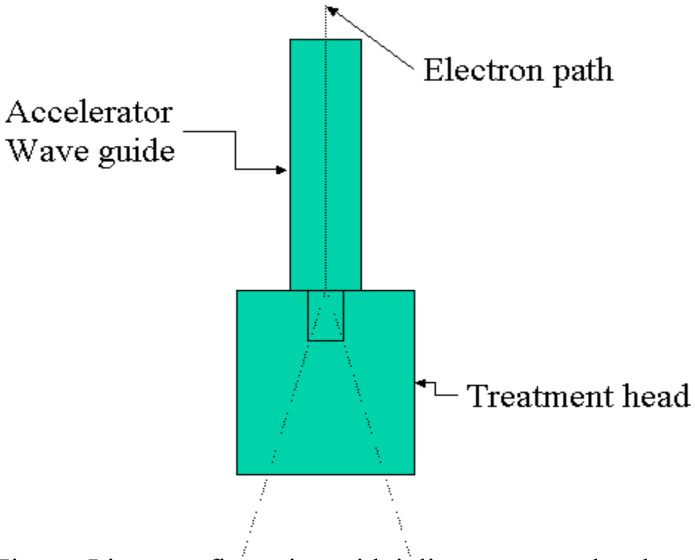


Figure: Linac configuration with inline treatment head.

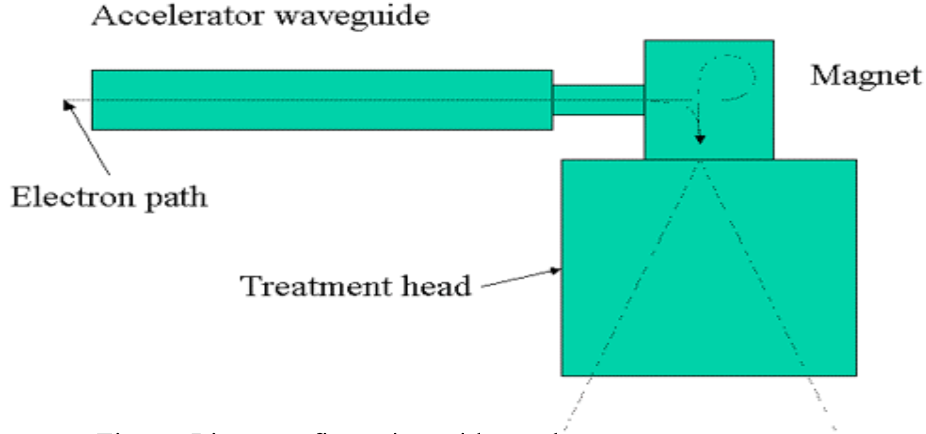


Figure: Linac configuration with accelerator structure at right angles to the treatment head. A 90°, or preferably 270°, bending of the electron beam is required.

- Besides the bending system, the treatment head contains the beam production system consisting of the scattering foil and beam shaping elements for electron beam production, or a target, flattening filter and beam shaping elements for the generation of X-ray beams.

The Treatment Head

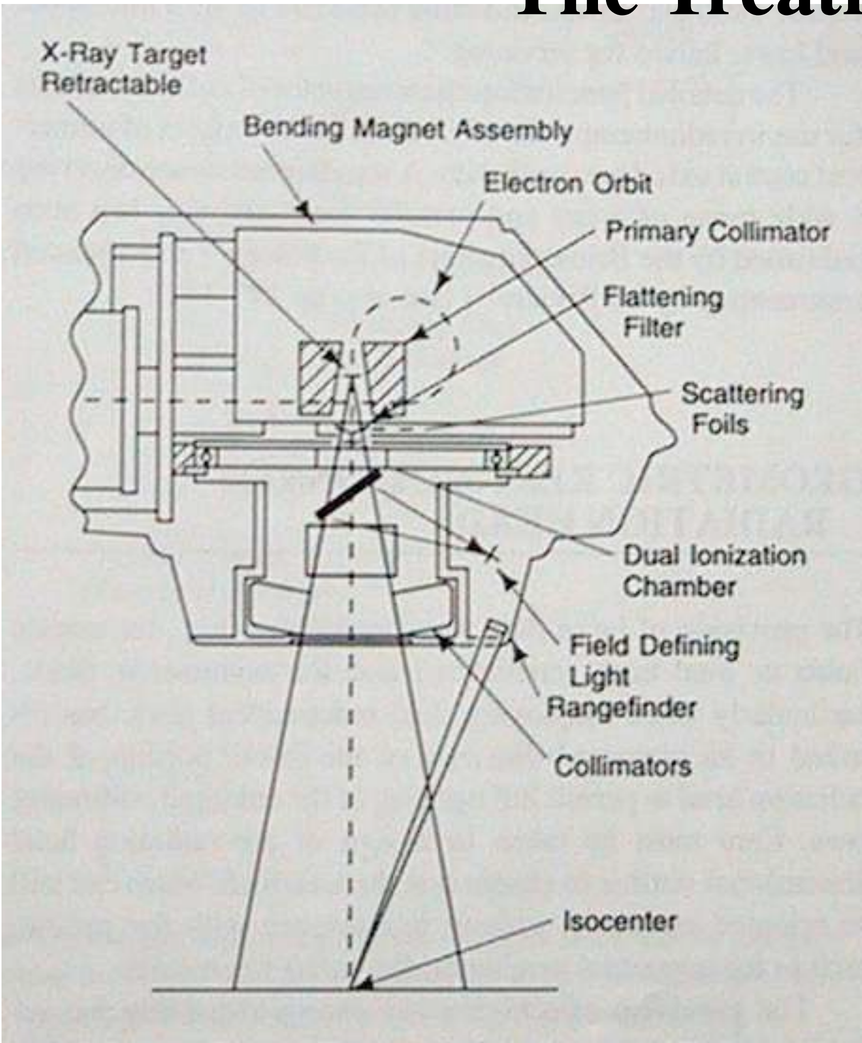
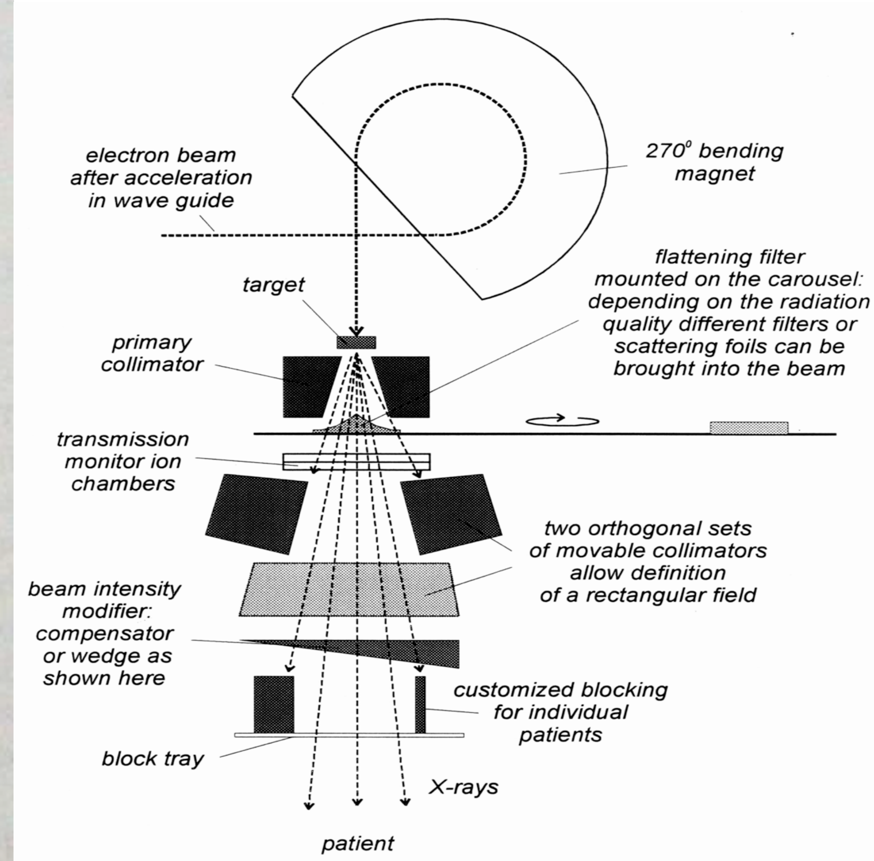


FIGURE 8-1 · Clinac 18 Treatment head. (Courtesy of Varian)



From: Medical Electron Accelerators

Karzmark et. al. 1993

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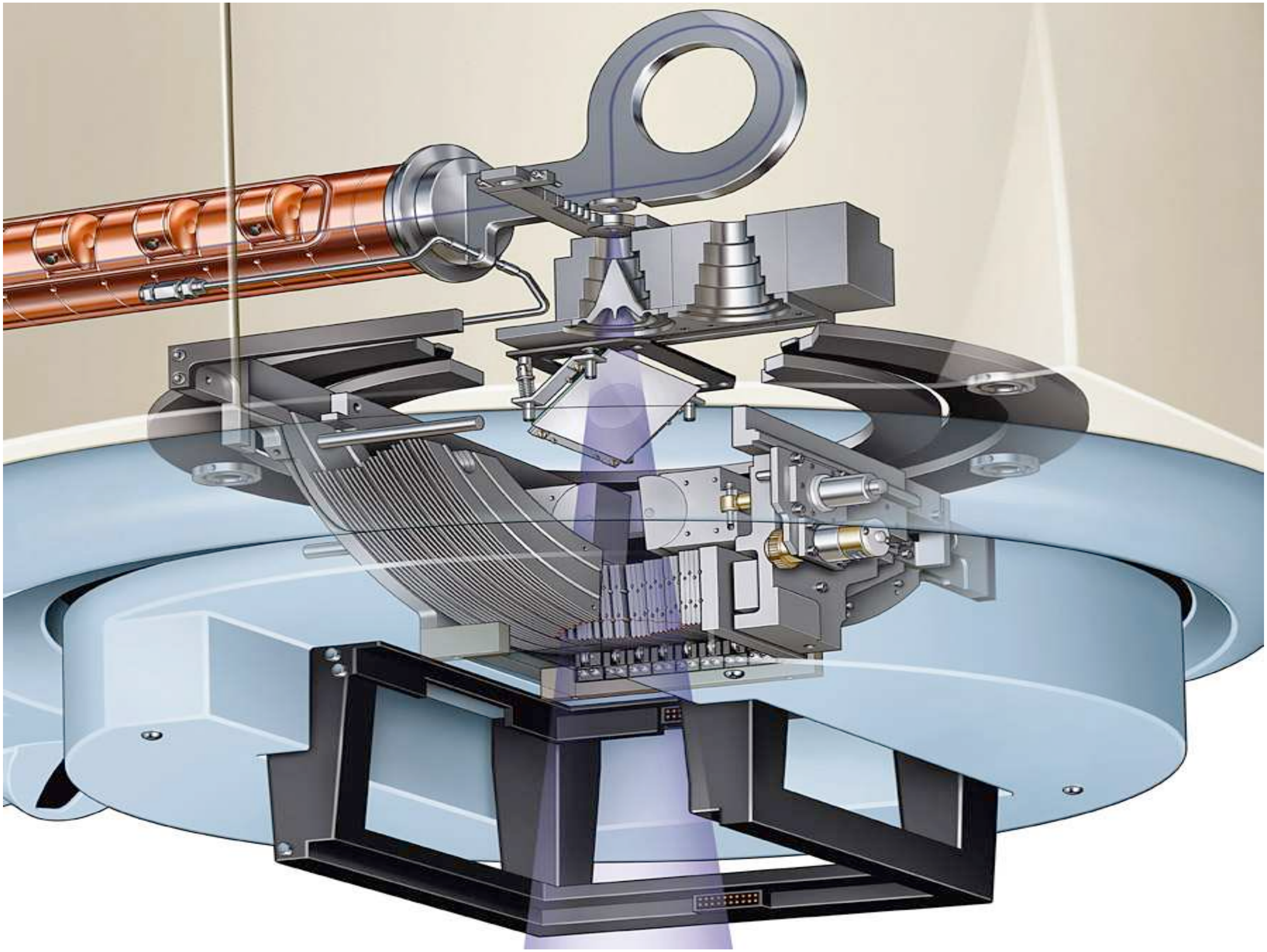
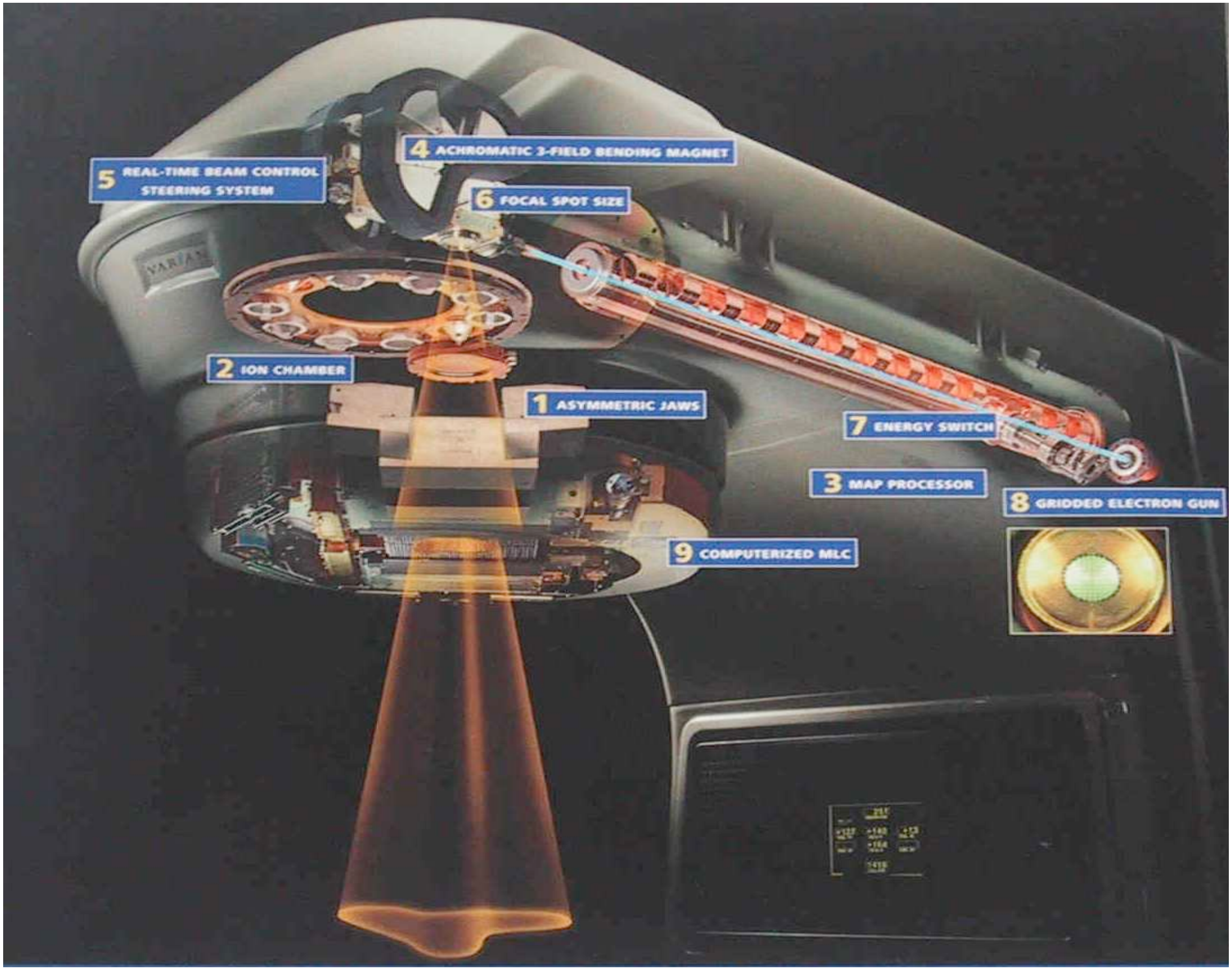




4 ACHROMATIC 3-FIELD BENDING MAGNET
5 REAL-TIME BEAM CONTROL STEERING SYSTEM
6 FOCAL SPOT SIZE
VARIAN
2 ION CHAMBER
1 ASYMMETRIC JAWS
7 ENERGY SWITCH
3 MAP PROCESSOR
8 GRIDDED ELECTRON GUN
9 COMPUTERIZED MLC

Beam Production

- Medical linacs are used to provide beams of electrons as well as X-ray s. X-ray beams are used to treat deep seated tumors, electron beams are used to deposit their energy nea r the surface of the patient.
  - **Electron beams**

    An appropriate scattering foil position for the electron energy to be used is placed in the beamline. Electrons penetrating the foil are scattered and form a broadened electron beam. The ion chamber monitors this beam. An electron applicator for the field size chosen, into which a shaped lead cut-out can be inserted defines the final electron field size and shape.Most linacs employ a pair of metallic foils to scatter the beam output from the bending magnet.
  - **X-ray beams**

    the electrons strike a target made of a heavy metal. This loss of kinetic energy is restituted as high energy photons. This effect is called Bremsstrahlung. For low and medium energies tungsten targets are employed, whilst for high energy X-ray beams (above 15 MV) targets with lower Z-material (e.g. Mo or Ag) are used.

Ion Chamber

- Radiation exposure is controlled by two integrating transmission ionization chamber systems.
- These are **the primary system** and should terminate the exposure at the correct number of monitor units (MU's)
- These also steer the beam via a feedback loop

Note on Monitor Units: Dose monitors are calibrated on site so that a monitor unit (MU) read out on the control console is uniquely & unambiguously related to the absorbed dose in a phantom under prescribed conditions

e.g. 1 MU may equal 1cGy for a 10x10-cm field on axis at 100-cm SSD and 10 cm depth (or at D_{max}) in a water phantom

Ion Chamber

The transmission ionisation chamber of a contemporary high energy linac is constructed of several plates or electrodes, whose areas may be divided into sectors so as to serve two different monitoring purposes:

1. Dose rate and integral dose of the x-ray and electron treatment beams

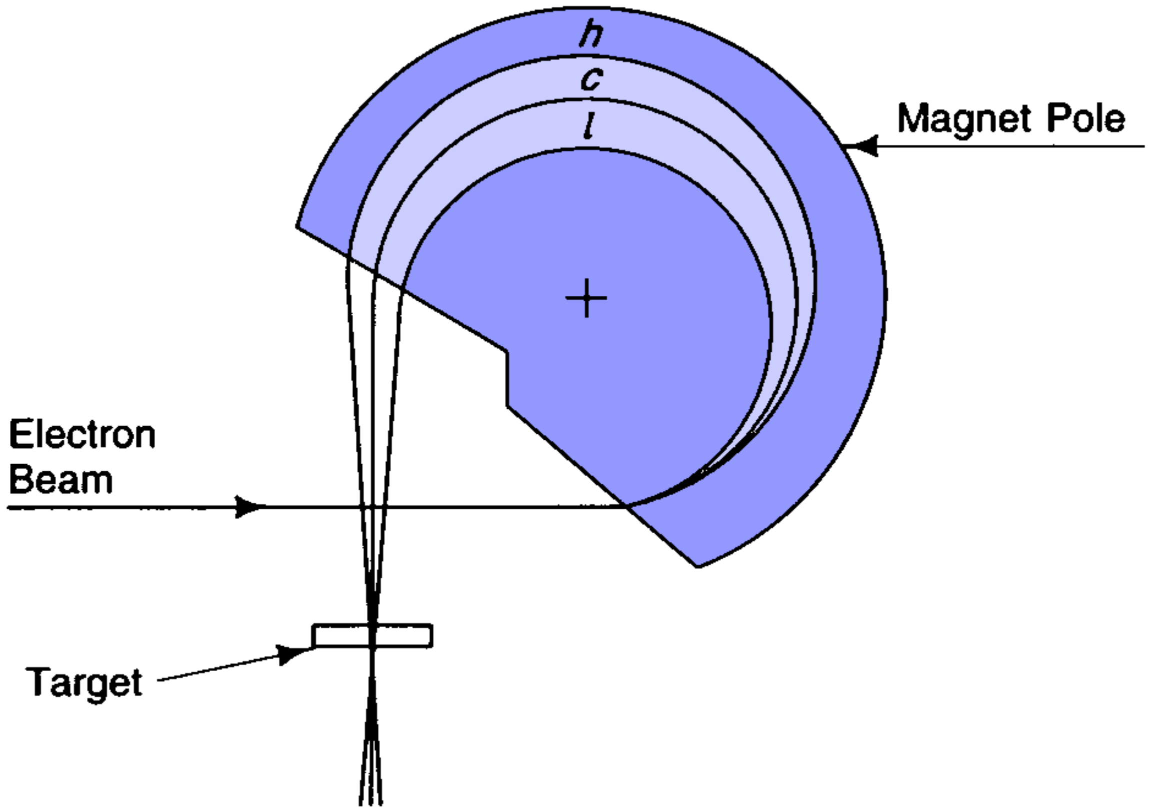
2. Angular and radial (positional) distribution of the radiation in the treatment beam

In addition the resultant electrical signals are used in automatic feedback circuits to steer the electron beam through the accelerator guide & bending magnet onto the target (or scatterer) to ensure treatment beam flatness and symmetry

Electron Beam Bending

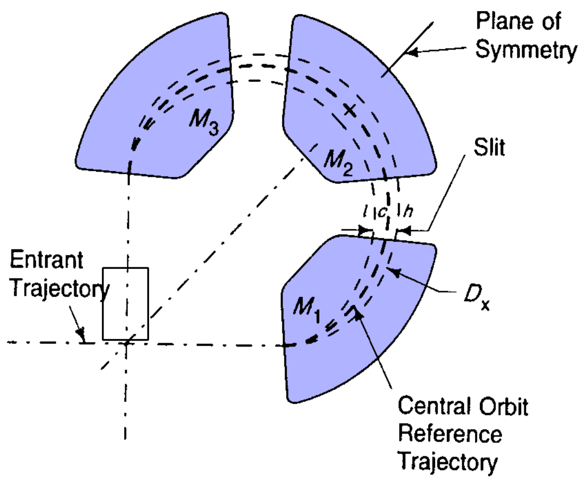
- Deflects beam in a loop
  - ~ 270°
  - Provides focusing for spread of energies in beam
    - Simple 90° magnet defocuses spread of energies
  - Small focal spot
    - Small penumbra

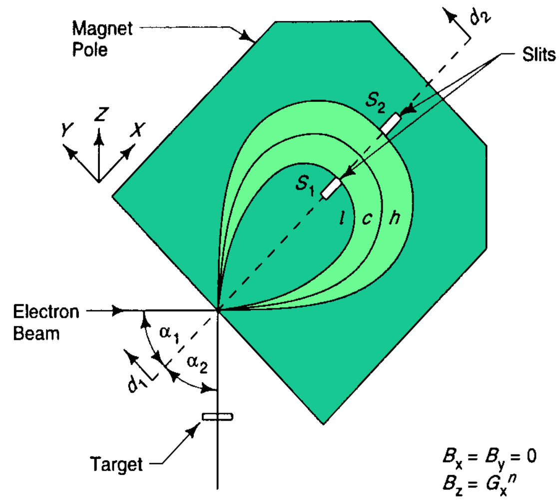
Electron Beam Bending - 270^{o}

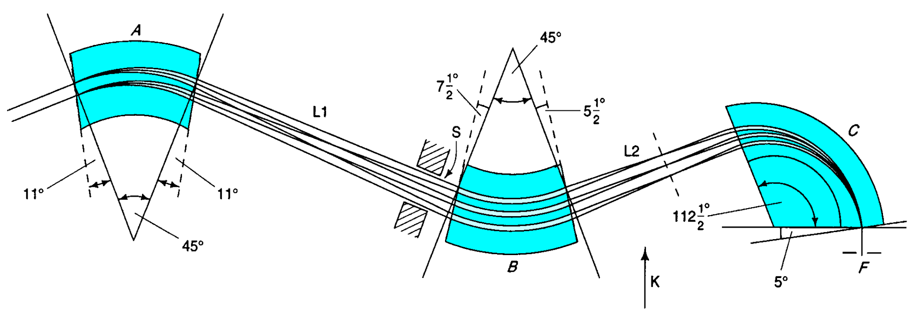


Spread in angle of exit beam produced by 270^{o} singly achromatic "triple-focus" bending magnet due to energy spread l (low E component),to h (high E component), of entrant beam

Achromatic Magnet Designs







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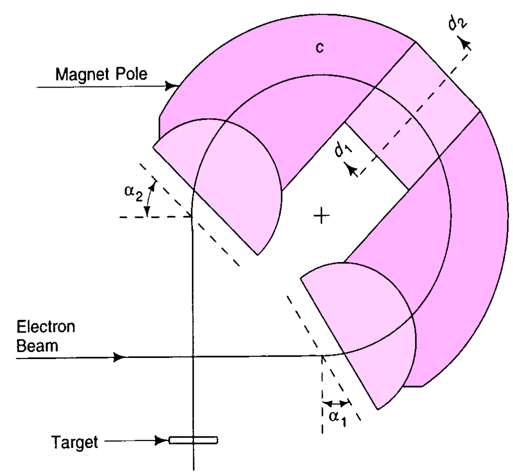
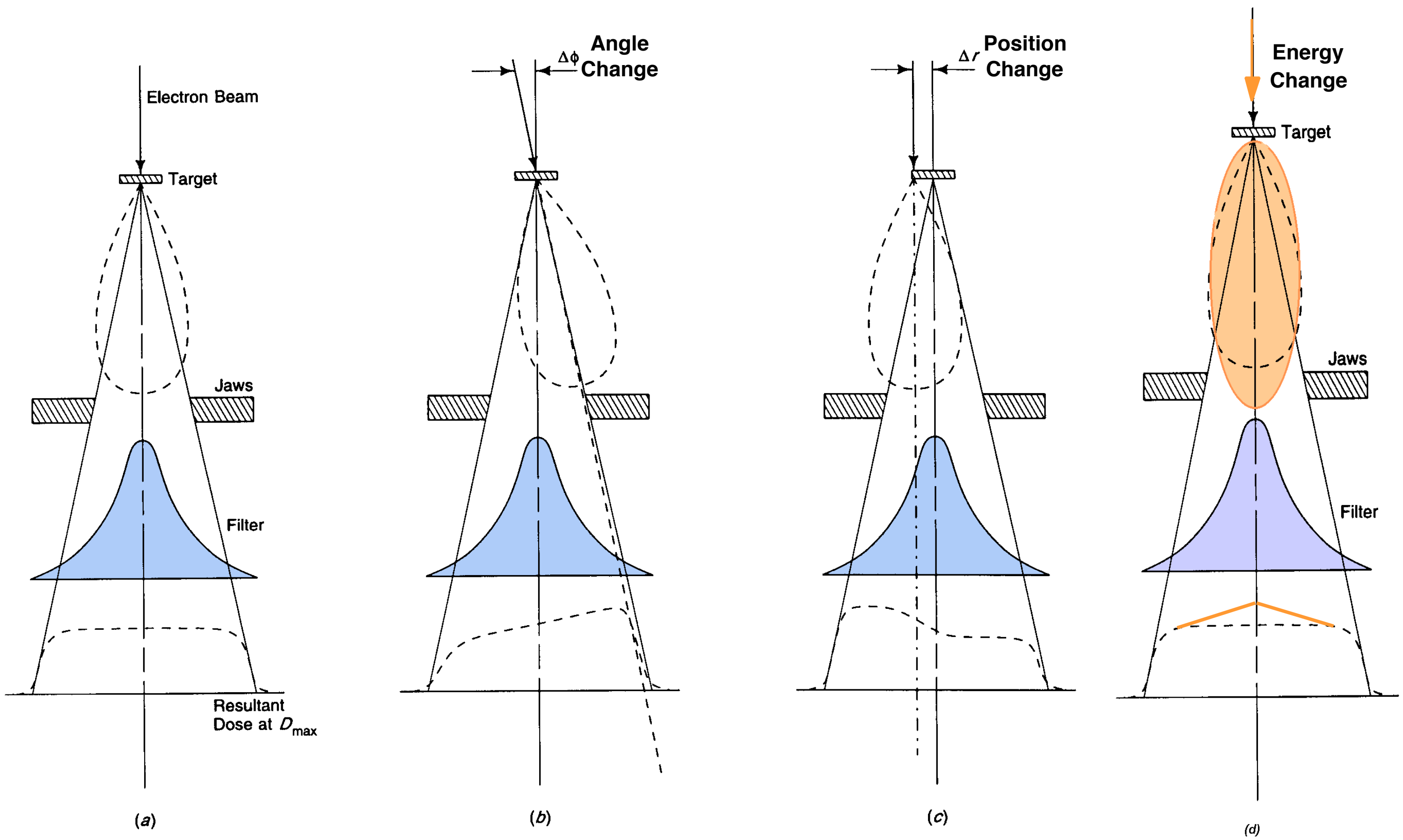


Bending Magnet

- In the bending magnet, only e's with the correct energy go out through the beam exit window.
- An electron with an energy too far from required scrape the envelope walls generating heat which requires the magnet to be cooled by water.
- The magnetic field needs to be adjustable to select the required energies. This is accomplished using an electromagnet.

Beam Symmetry and Flatness



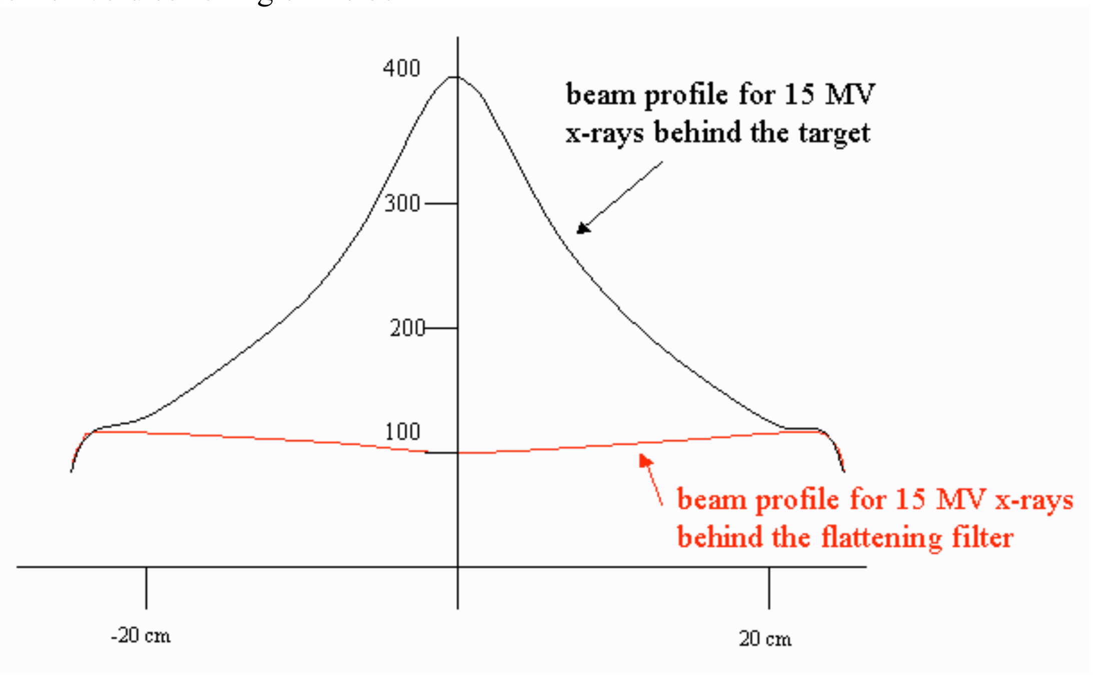
Beam flattening filter

The bremsstrahlung photons emerging from the target are mainly directed in the same direction as the incoming electrons.
This forward-peaking increases with beam energy.

The beam flattening filter is a cone-shaped device which differentially absorbs the radiation towards the beam centre and is designed to generate a uniform dose distribution across the X-ray field.

The filter substantially reduces the dose rate at the beam centre. Especially for high energy and large fields, a large amount of the photon fluence is absorbed in the flattening filter. The dose rates available from modern linacs are sufficiently high to compensate for this attenuation. They still have a useful output in the flattened field of several hundred cGy/min 1 m from the target.

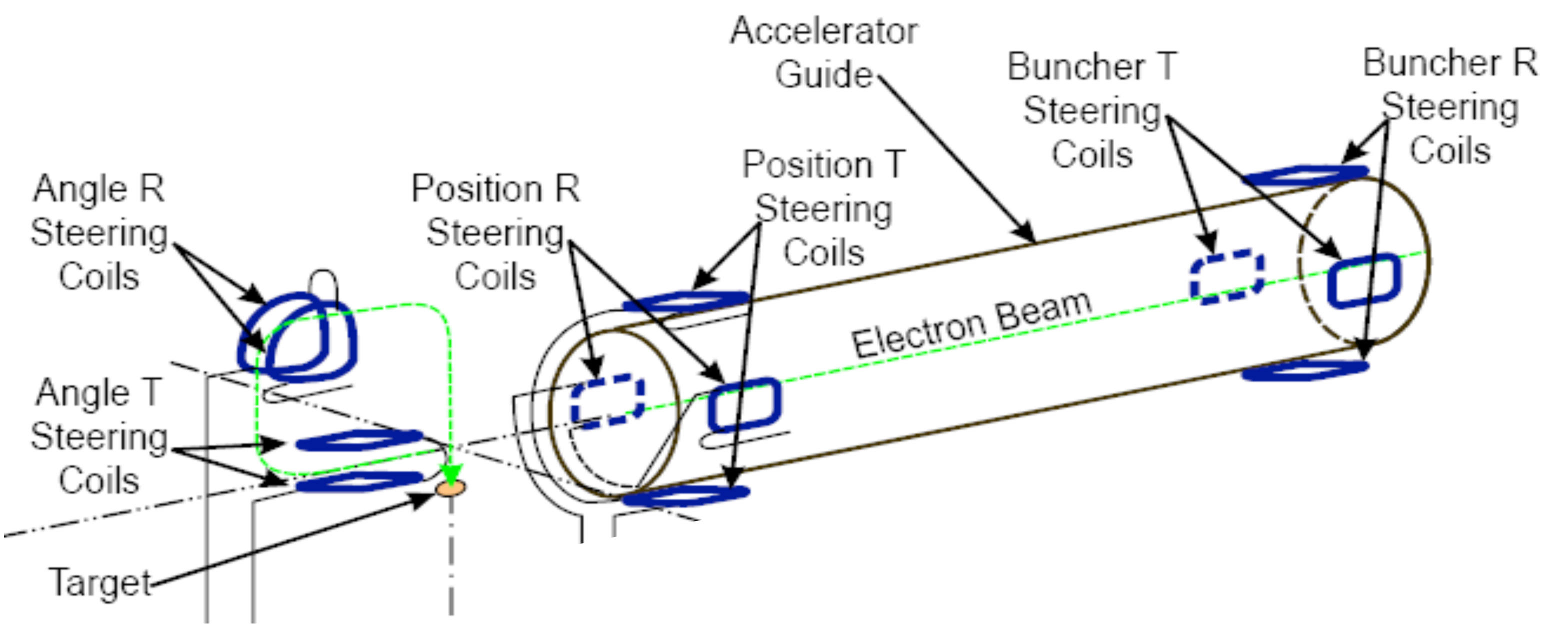
The beam flattening filter also acts as an energy filter and modifies the photon spectrum. It is essential to select the appropriate material for the flattening filter in order to avoid softening of the beam



Beam Steering

- The bending magnet is aligned in the factory to give the correct beam alignment for the high energy photon beam
- However, the beam must also match for lower energy photon beam and for the electron beams. Hence, a small beam correction is required in the waveguide
- 2 steering coils are added near the end of the waveguide to accomplish this.

• Steering coils for fine-tuning beam position and beam angle



Electron Beam Steering

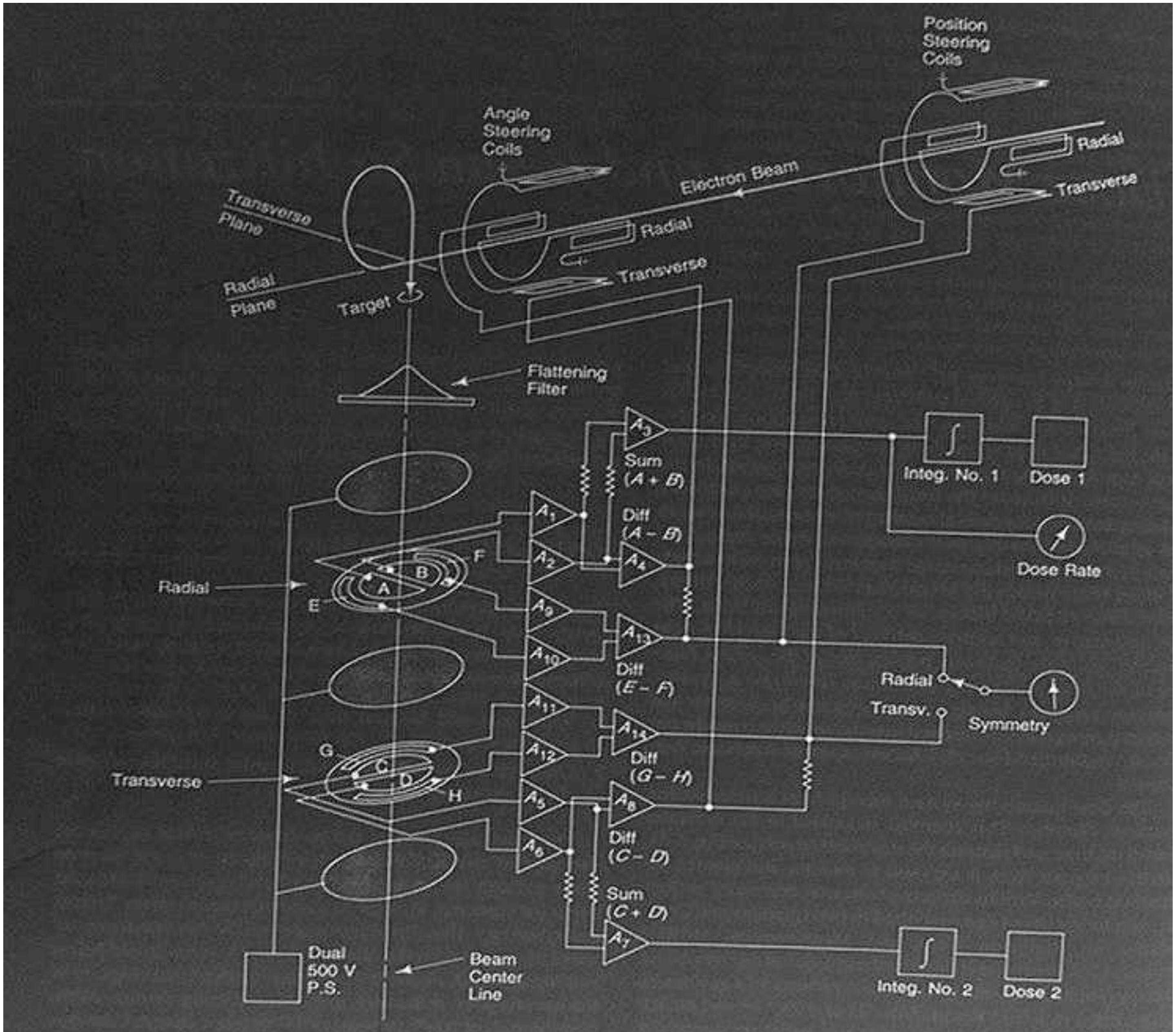


FIGURE 9-1 · Five-electrode ionization chamber with simplified block diagram of dosimetry and beam steering system. The radial and transverse coordinate planes of the bending magnet orbit are identified in the upper left. The radial angle steering coils are actually located in the bending magnet, as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

From: Medical Electron Accelerators

Karzmark et. al. 1993

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Radiation Beam Shaping

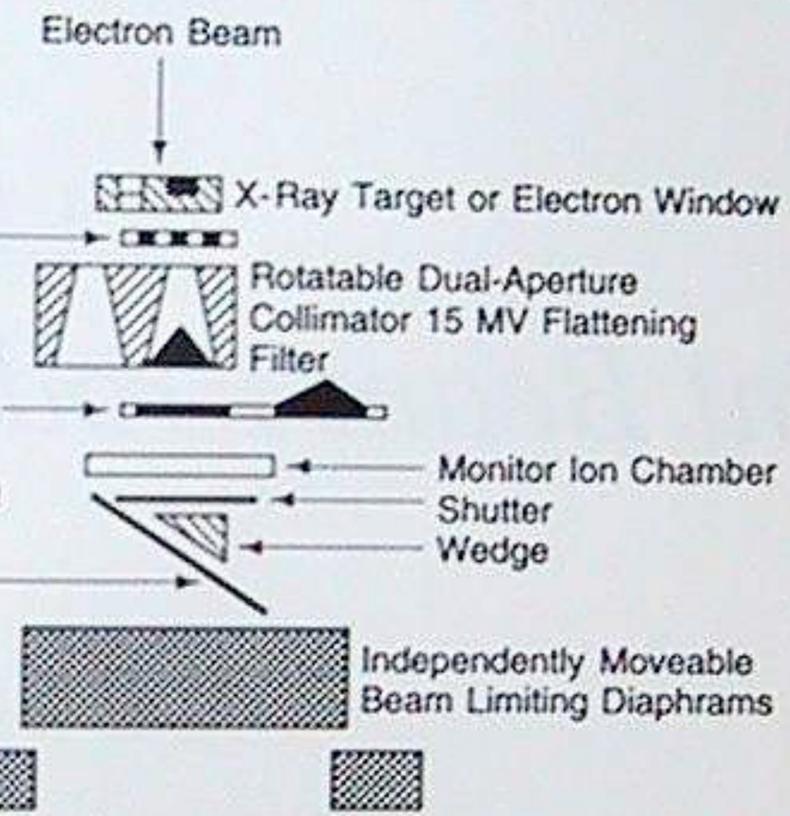


FIGURE 8-2 · Philips SL25 treatment head. (Courtesy of Philips Medical Systems.)

From: Medical Electron Accelerators
Karzmark et. al. 1993
McGraw-Hill

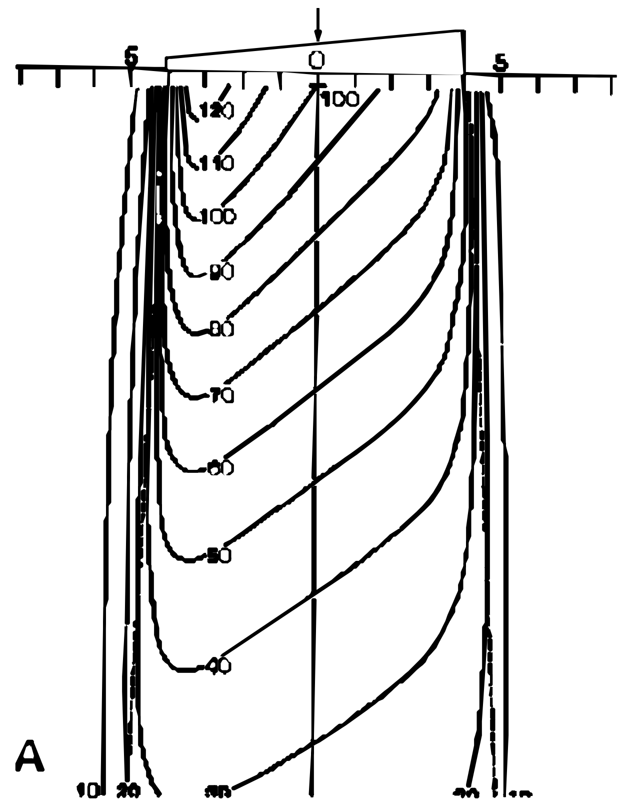
Important Accessories

- Wedges
- Dynamic wedges
- Blocks
- Multileaf Collimator (MLC)
- Electronic Portal Imaging (EPID)

Wedges

angle

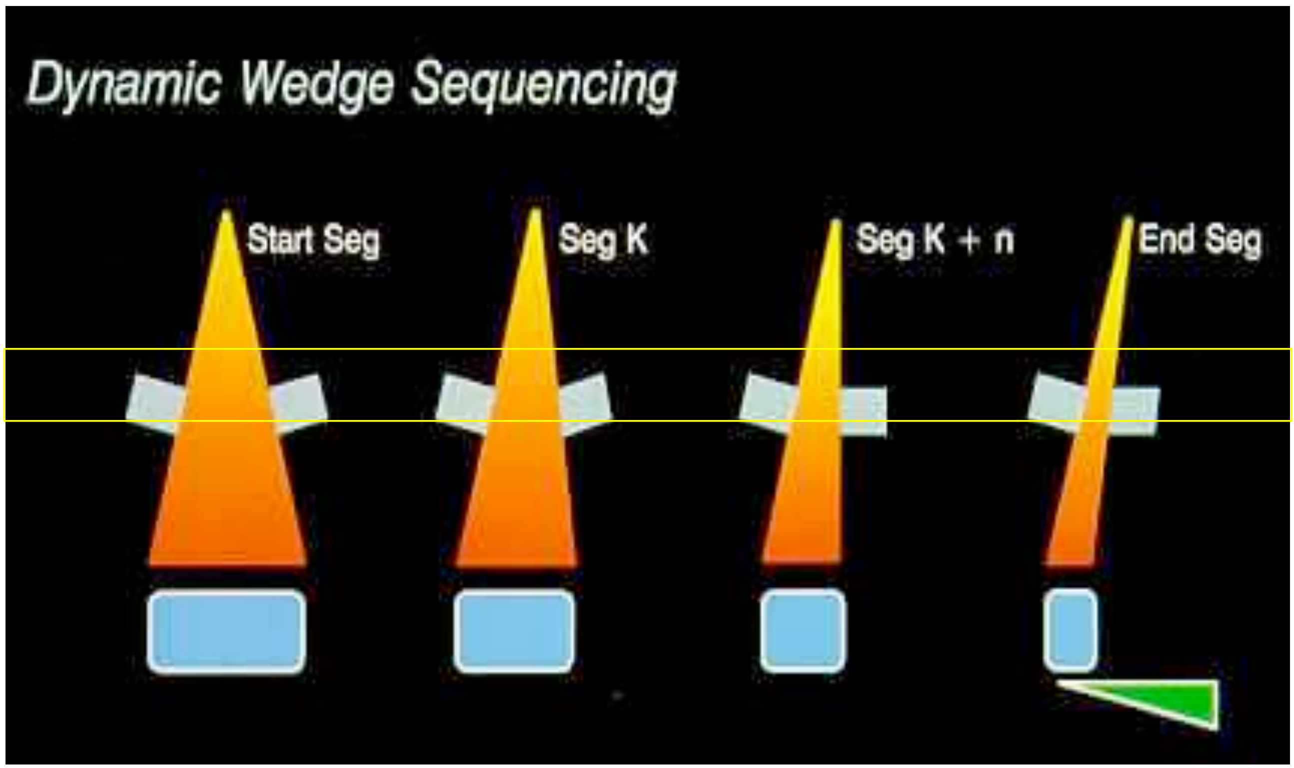
- Wedges
  - 3 or more fixed wedges
  - auto-wedge
  - dynamic wedge
- Modify dose distribution



Wedges

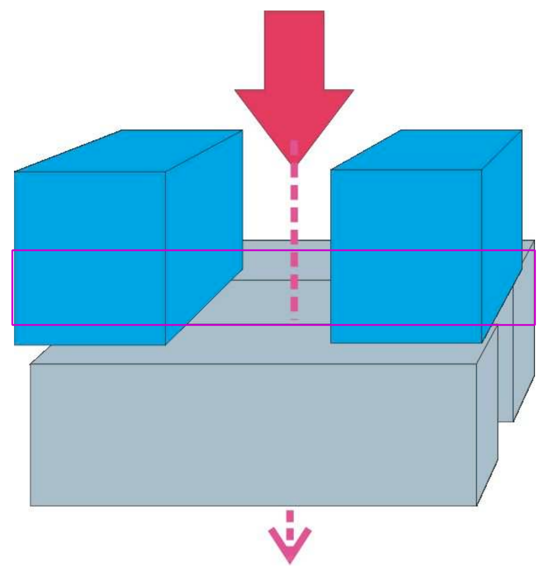
- ‘standard’ treatment accessory
- required for example in breast and head and neck treatment
- dynamic wedge most popular because:
  - no weight
  - any wedge angle possible
  - but difficult to commission

- Dynamic wedge



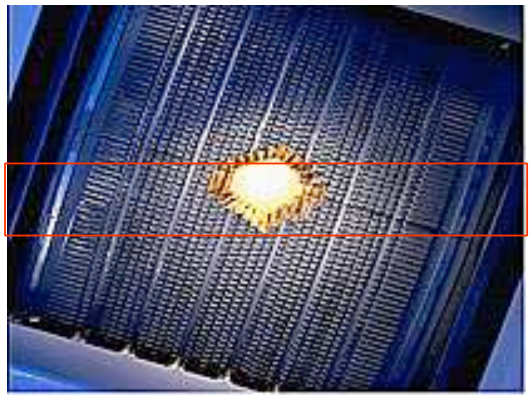
X-ray Collimators

- X-ray Collimators may be (1)
  - rectangular (conventional)
    - the transmission through the collimators should be less than 2% of the primary (open) beam



- X-ray Collimators may be (2)
  - Multi-Leaf collimators (MLC)
    - the transmission through the collimators should be less than 2% of the primary (open) beam
    - The transmission between the leaves should be checked to ensure that it is less than the manufacturer's specification

Siemens MLC



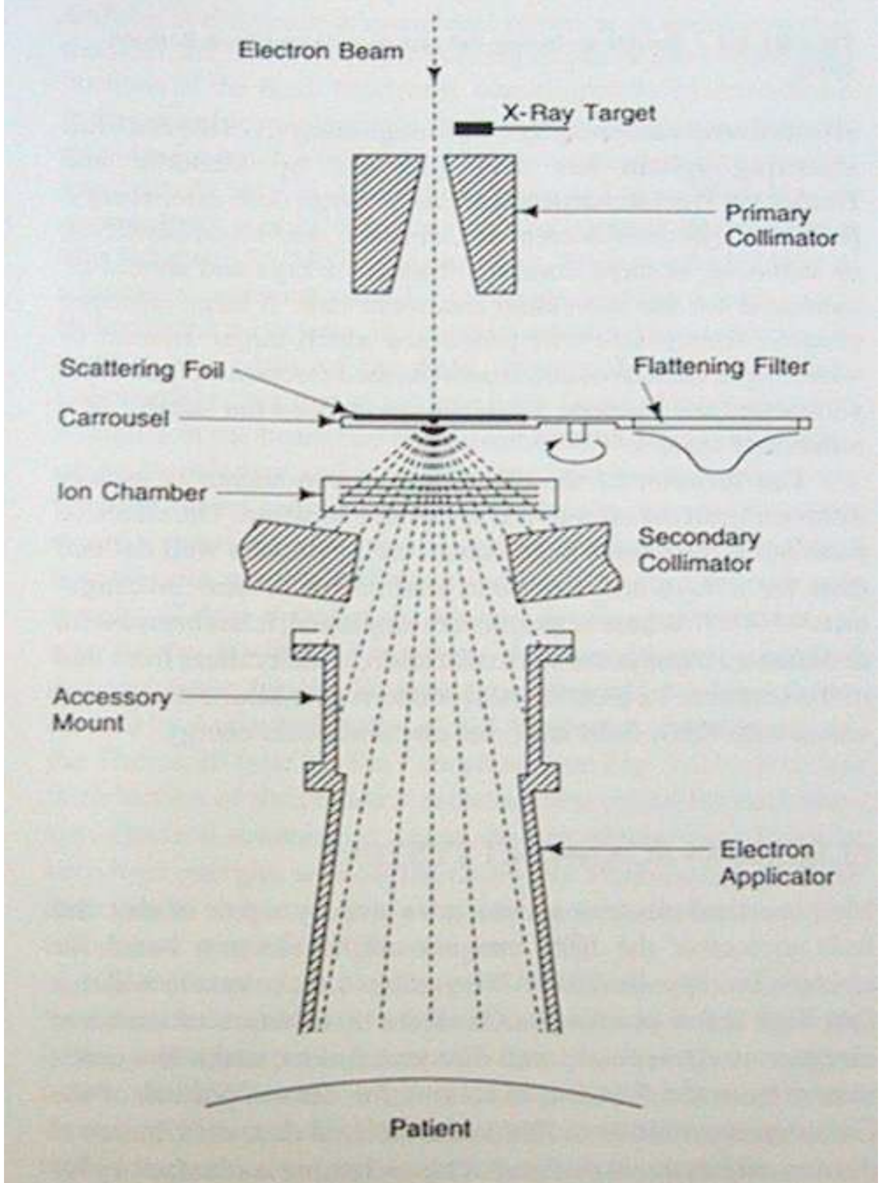


FIGURE 8-4 · Beam subsystem for electron beam therapy. Cross section view including central axis of the beam.

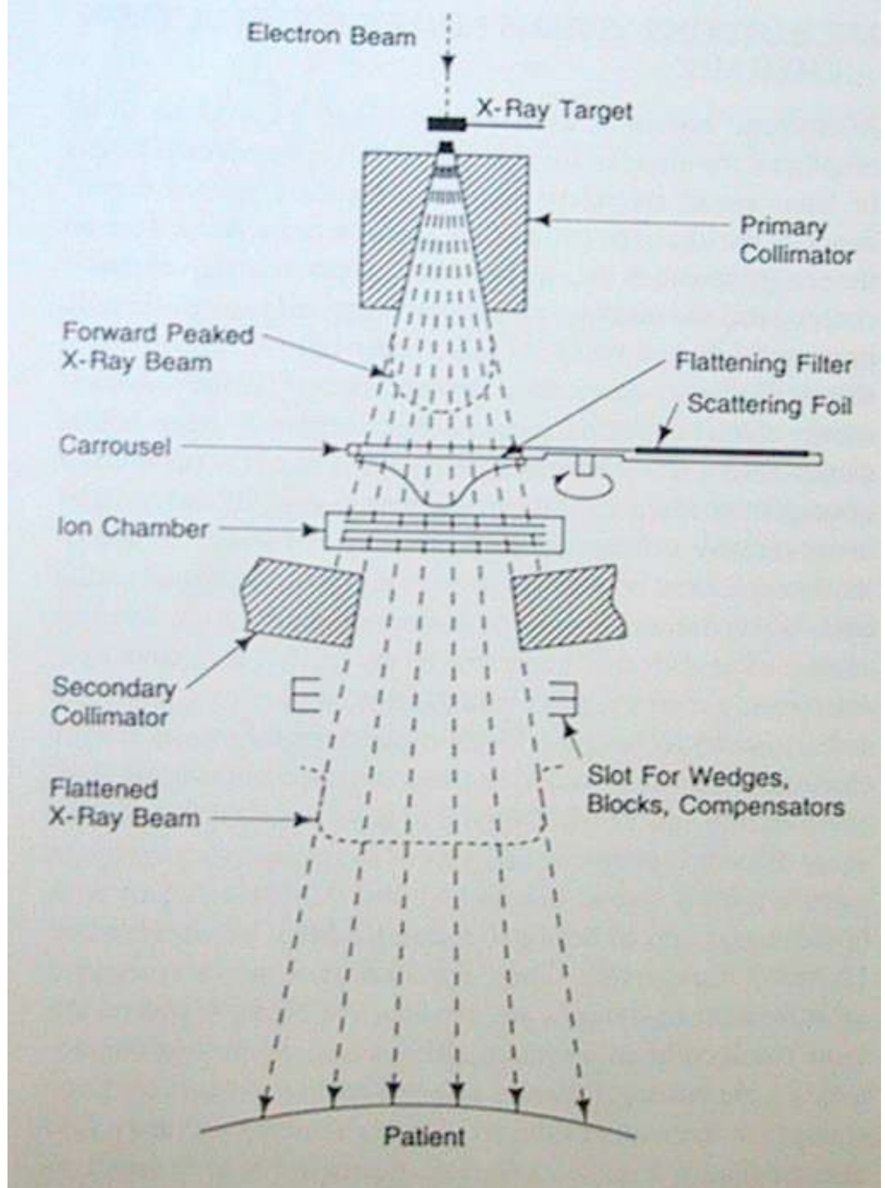


FIGURE 8-6 · Beam subsystem for x-ray beam therapy. Cross section view including central axis of the beam.

From: Medical Electron Accelerators; Karzmark et. al. 1993

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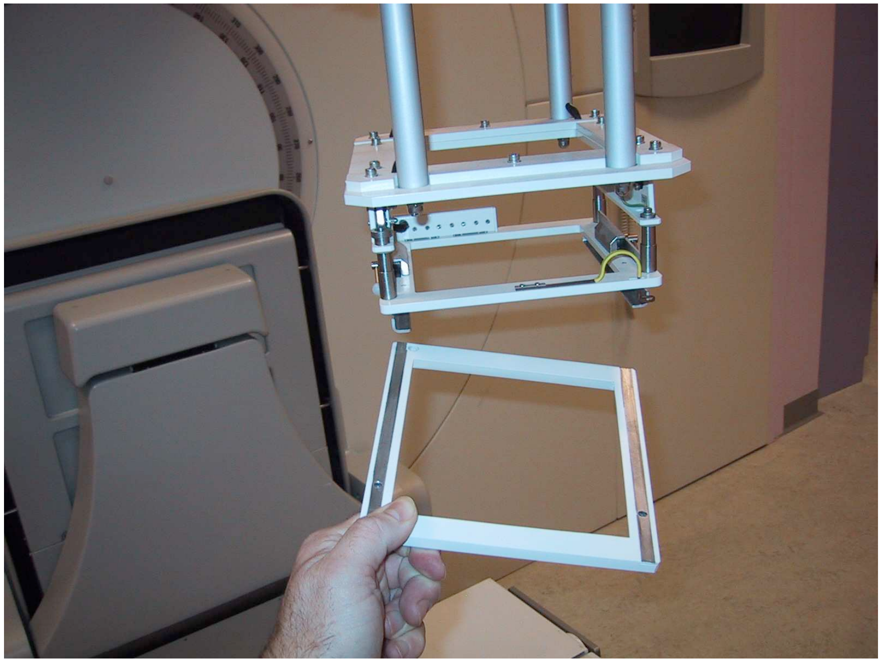
Electron Applicators

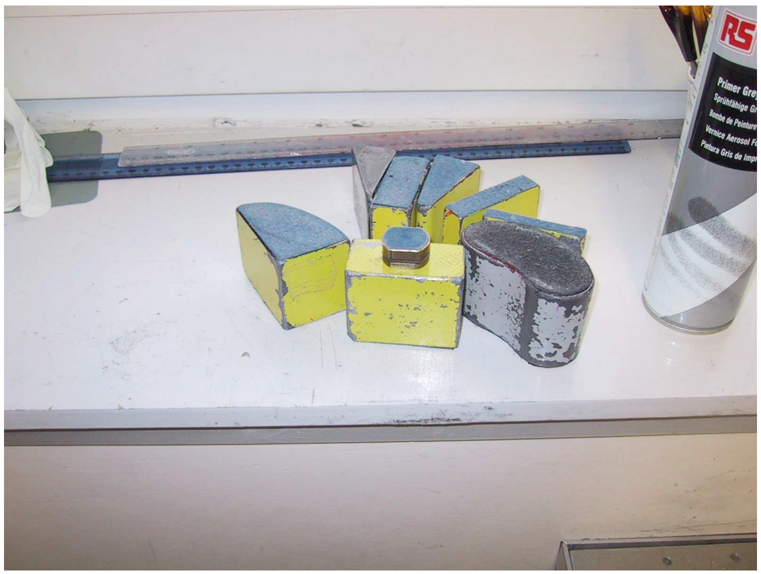
- Applicator Cut-outs
  - Standard
    - 10 x 10
    - 10 x 15
  - Custom
    - Mould room
    - Block cutter





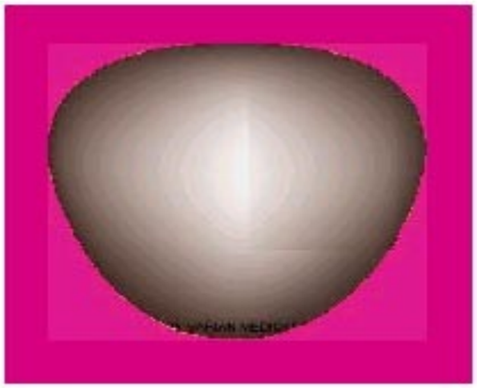
varian

Blocks

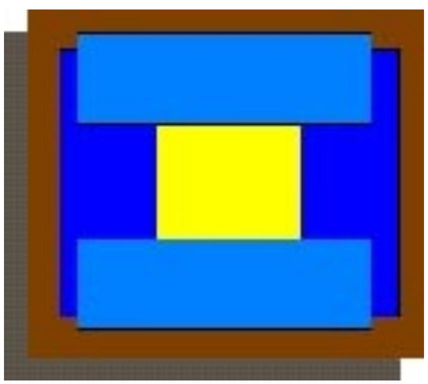


- Originally Lead
- Cerrobend
- Standard
- Customised
  - Mould Room

Conventional Radiotherapy - 1960s



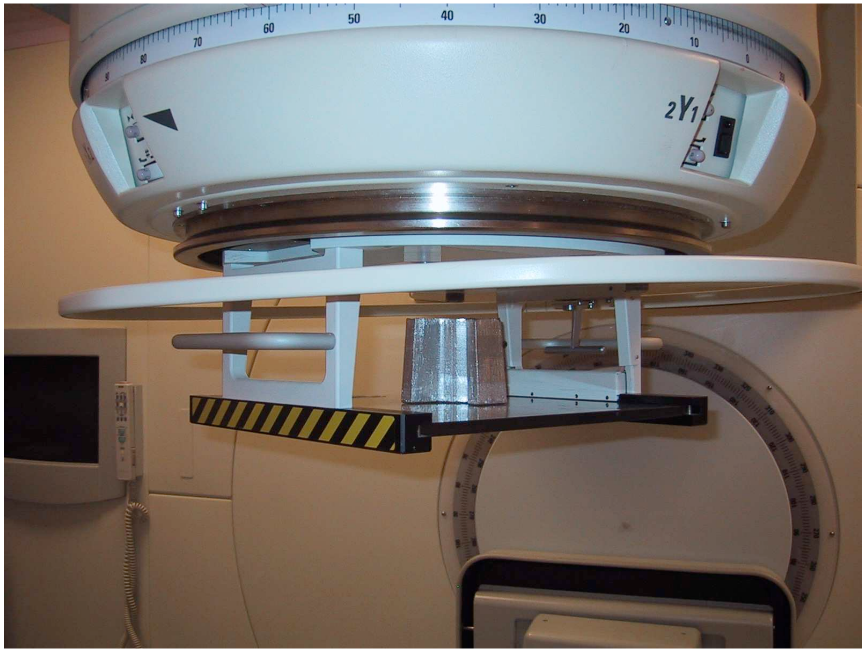
Pink = treatment field
or area hit by beam

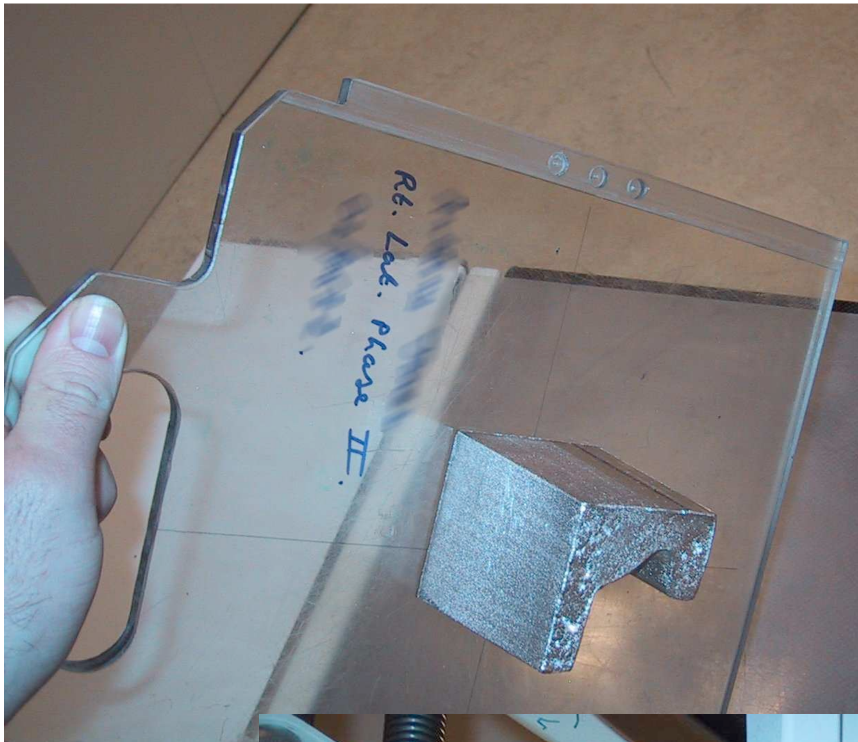


Primary collimator shapes
beam

- Simple treatment delivers uniform dose from 2-4 beam angles
- Beam shape is rectangular or square
- Beam hits healthy tissue as well as tumor
- Doses have to be kept low to minimize harm to normal tissue

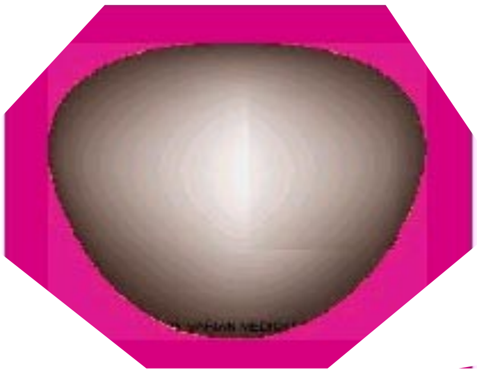
- Shape identified & marked on film
- Shape digitised
- Styrofoam block cut
- Alloy poured
- Blocks mounted on tray
- Verified for shape, size and position
- Used during treatment



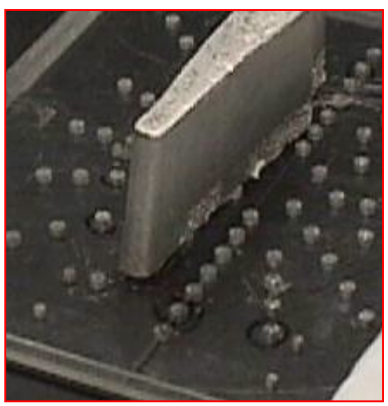


Custom Coding

Early Beam Shaping - 1970s



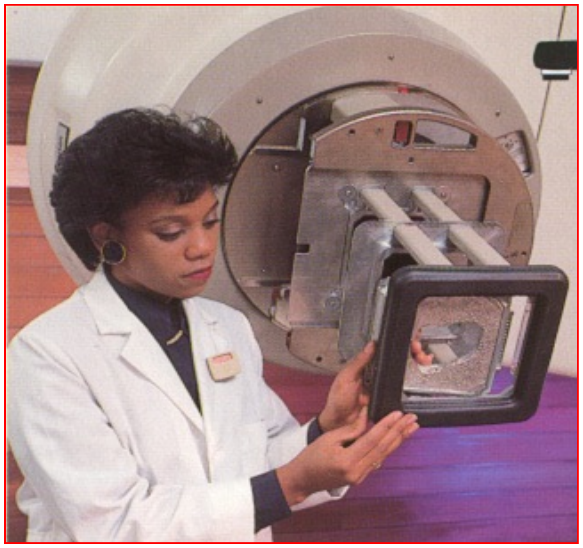
Roughly shaped treatment field

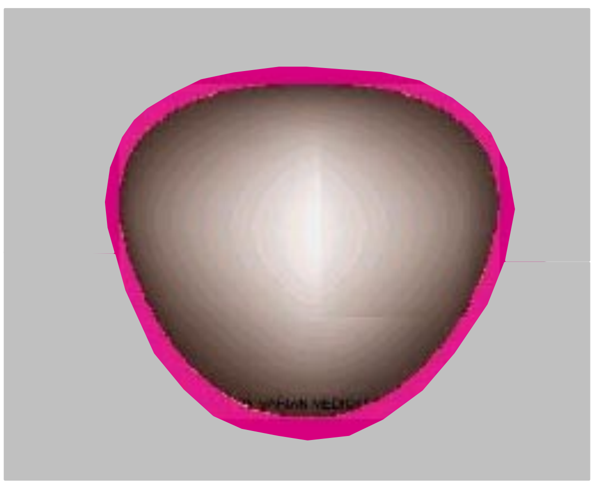


Wedge helps shape beam

- Blocks and wedges used to shape beams and begin sparing healthy tissue
- Blocks are changed by hand for each beam angle
- Labor intensive process requires therapist to visit treatment room repeatedly
- Typical treatments use 4 beam angles
- Dose still relatively low

3-D Conformal Radiation Therapy - late 1980s



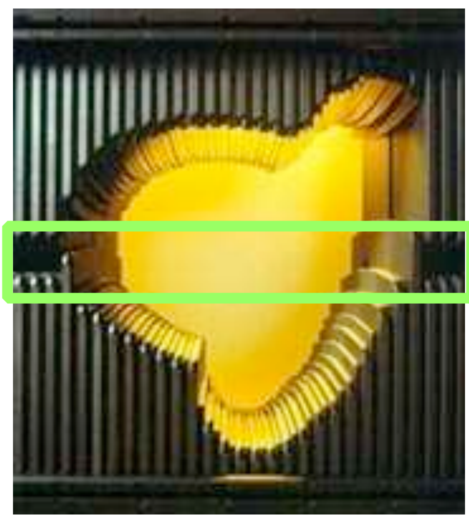


- Custom-molded block(s) match beam shape to tumor profile
- Beam shaping from multiple angles conforms radiation dose to tumor volume
- Typical treatments use 4-6 beam angles
- Dose still relatively low
- Blocks still changed by hand
- Still slow and labor intensive

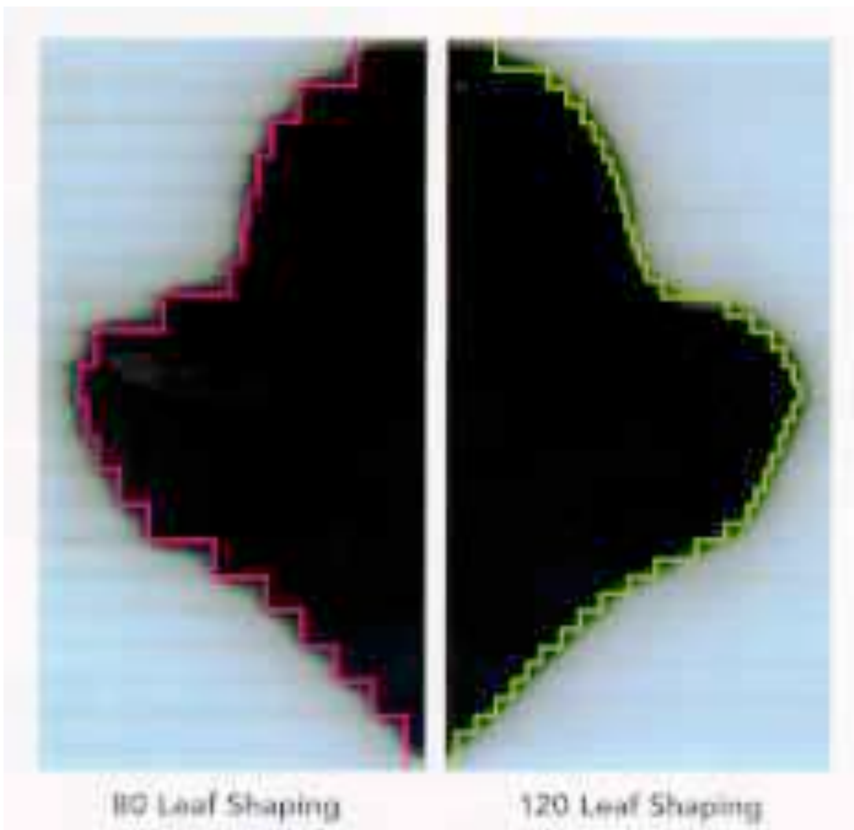
Multileaf Collimation

- Used to define any field shape for radiation beams
- Consists of two opposing banks of attenuating leaves, each of which can be positioned independently
  - Tungsten leaves
  - Individually controlled
  - Computer controlled

- Several variations to the theme
  - Different leaf widths (1– 0.3 cm)
  - 80 / 120 leaf collimators
- Replaces collimators or additional to normal collimators
- Conformal radiotherapy



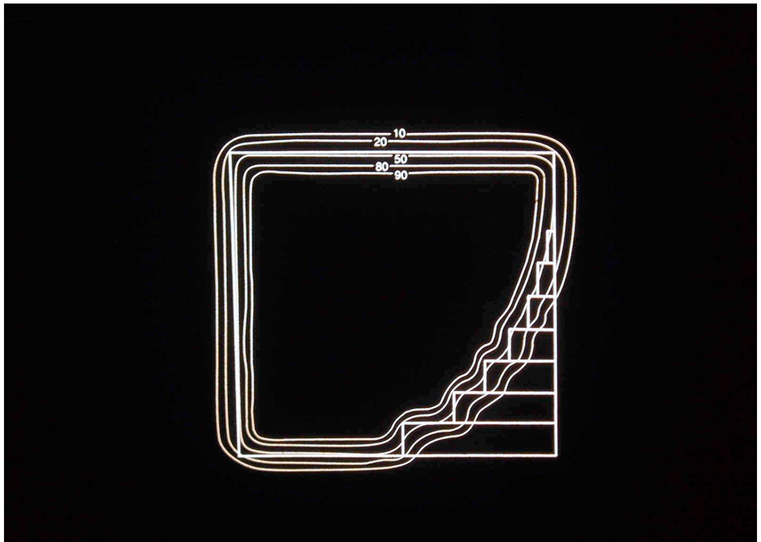
MLC

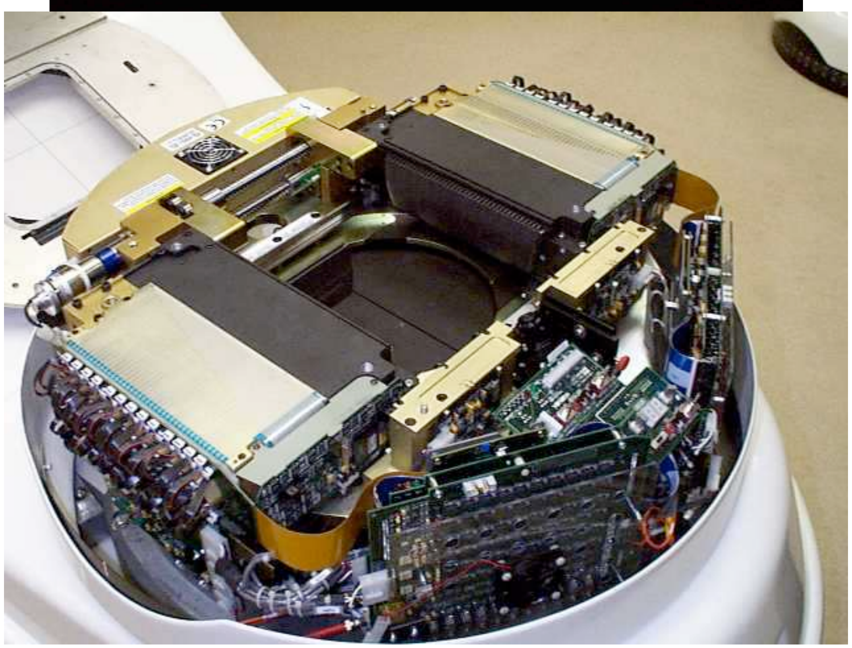


- The quality of the field definition depends on the thickness of the leaves
- There is always some interleaf leakage
- Typically the transmission through the MLC is larger than through a standard collimator

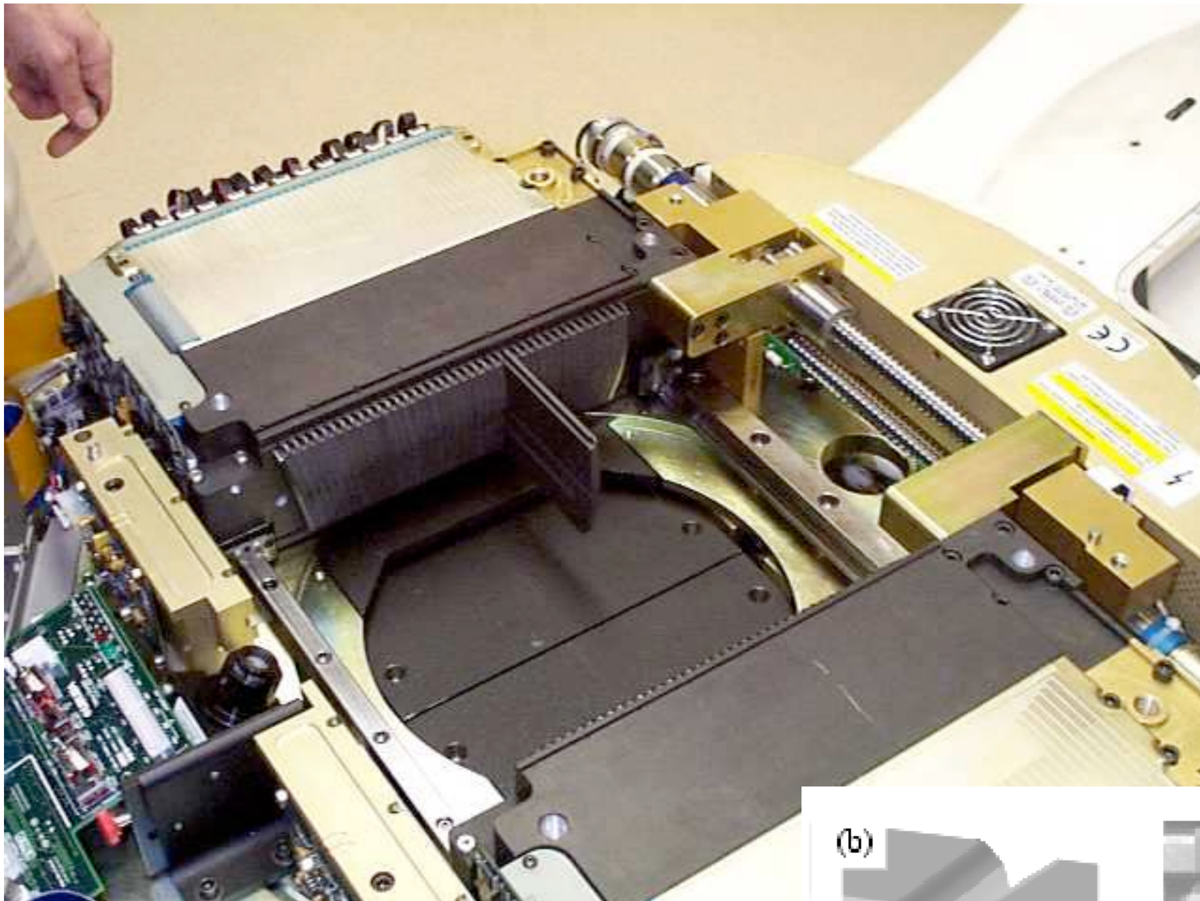
Note: Backup diaphragms will reduce interleaf leakage from the outermost leaf only

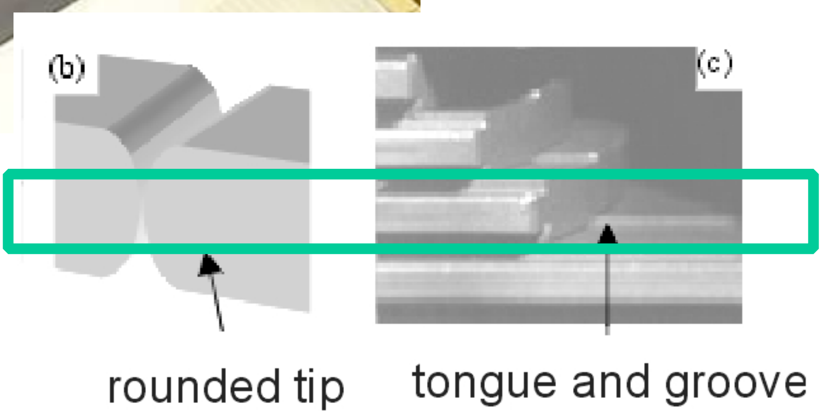
Multileaf Collimation





- 50 - >160 leaves
- 0.1-10mm width at isocentre
- Each leaf individually controlled




(b)
(c)
rounded tip
tongue and groove

MLC Leaf Shape

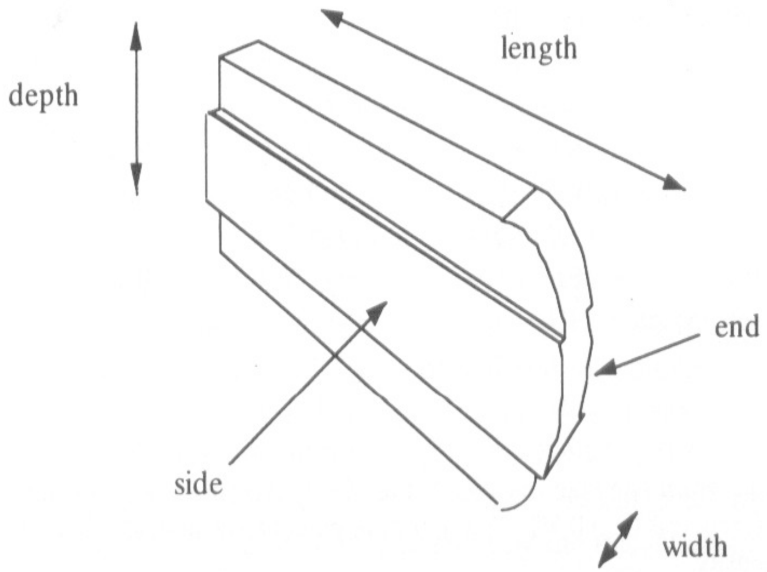
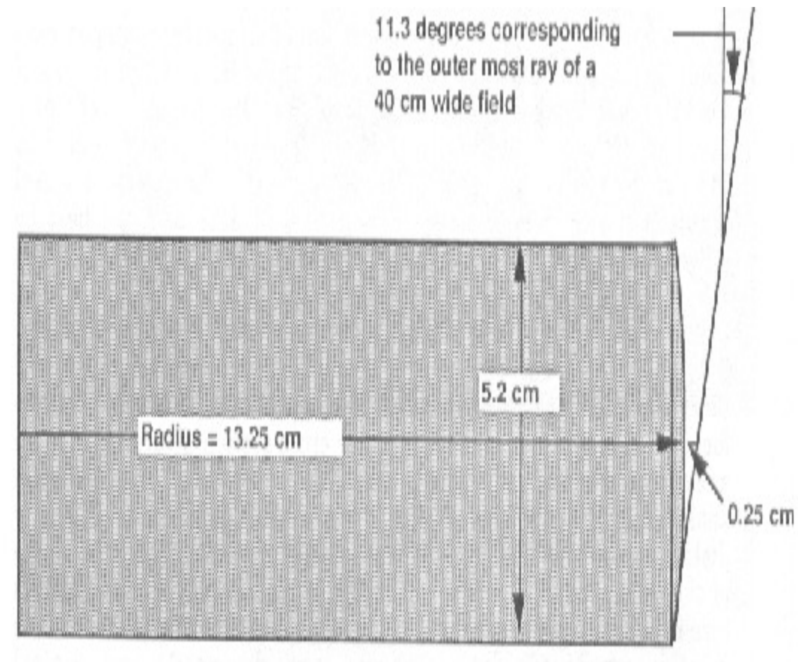


Figure 4. Schematic of generic MLC leaf illustrating leaf terminology. An example of a curved end and a stepped side.



Leaf Placement

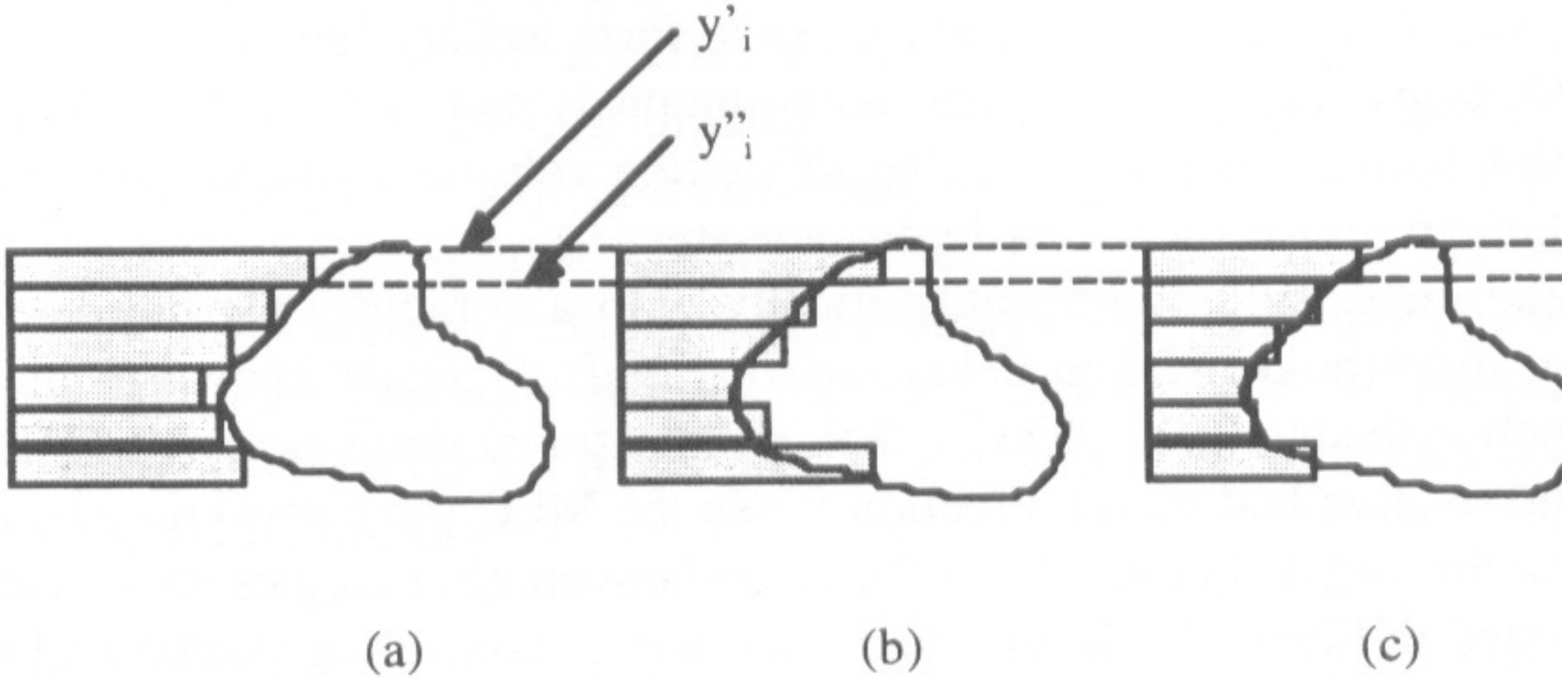
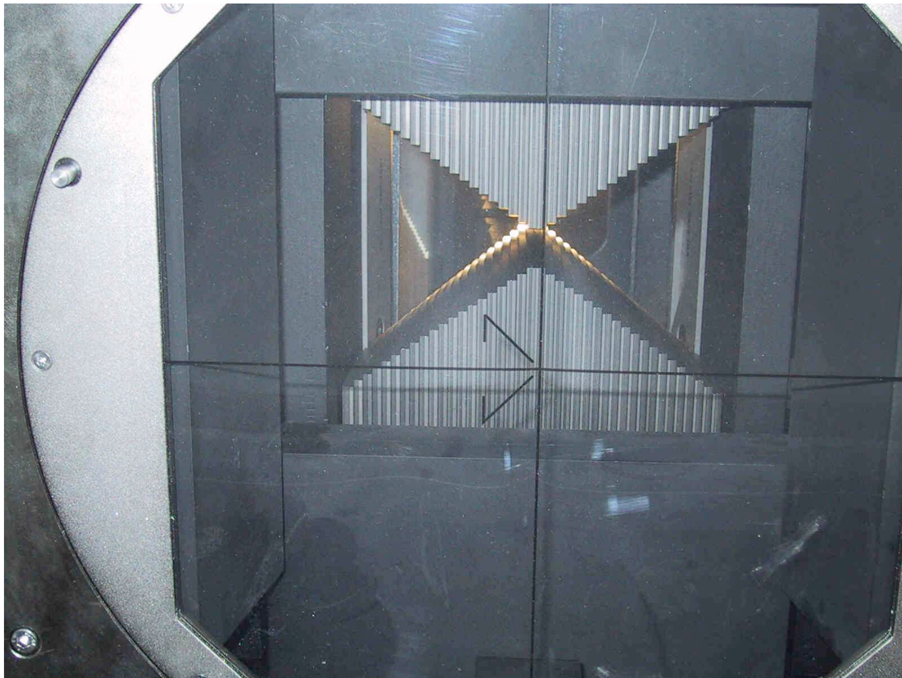
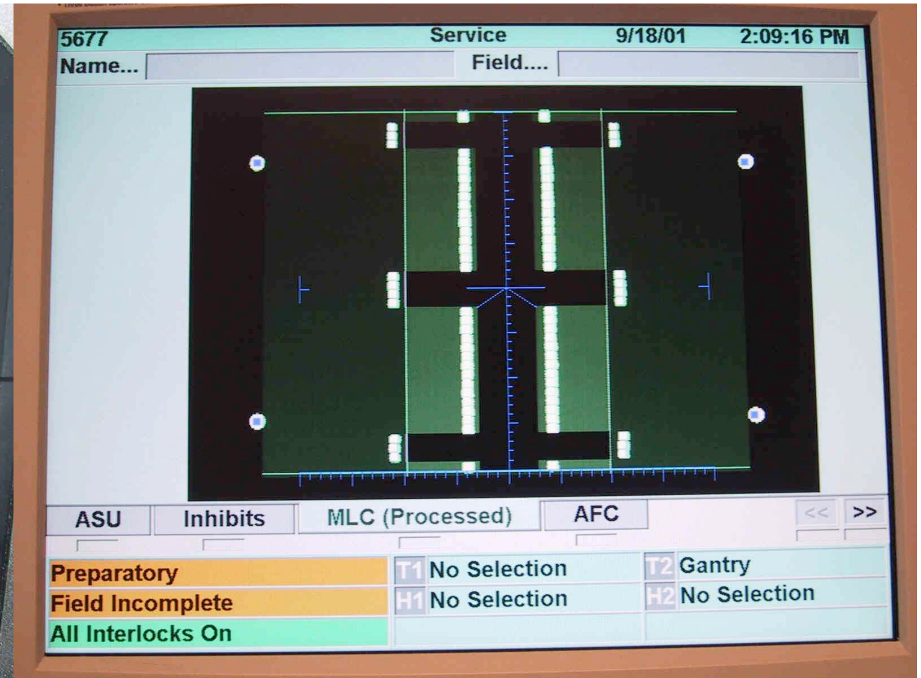
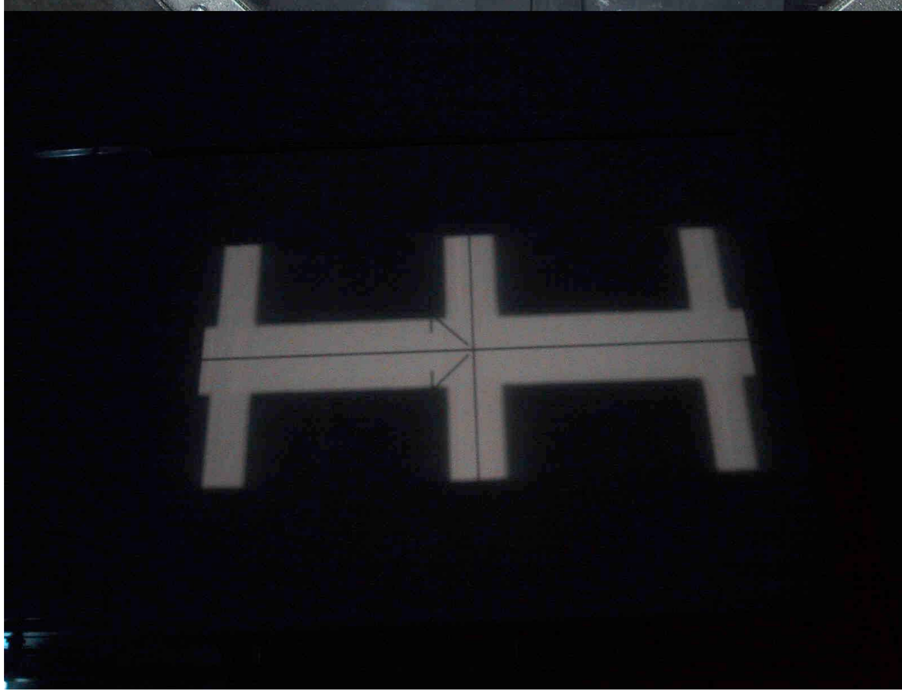
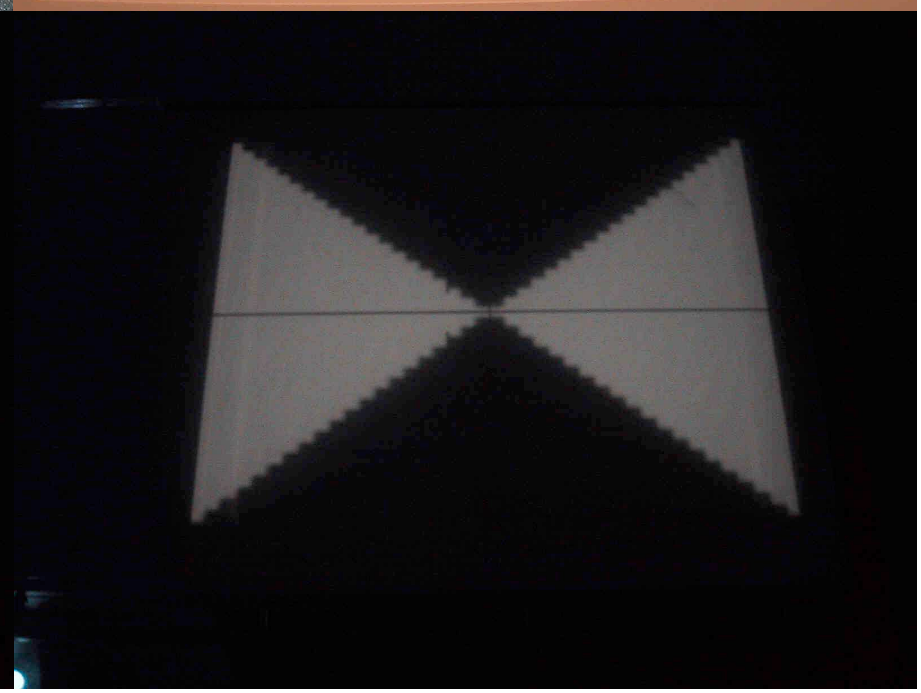


Figure 11. Illustration of three strategies for positioning MLC leaves at the nominal field boundary. (a) "out-of-field placement, (b) "in-field" placement, (c) "cross-boundry" placement.

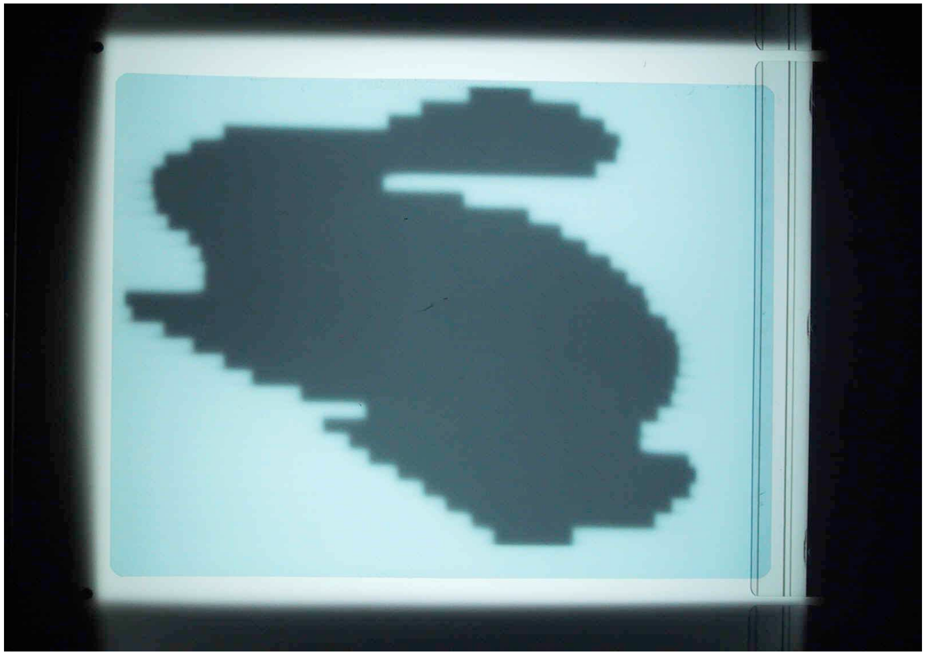


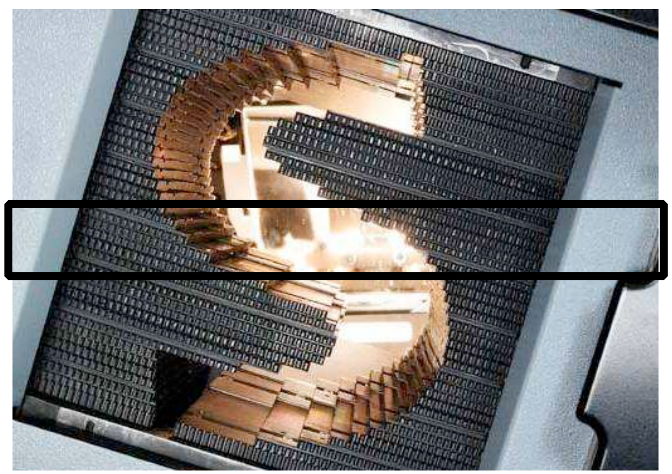

5677
Service
9/18/01
2:09:16 PM
Name...
Field....
ASU
Inhibits
MLC (Processed)
AFC
<<
>>
Preparatory
Field Incomplete
All Interlocks On
T1 No Selection
H1 No Selection
T2 Gantry
H2 No Selection



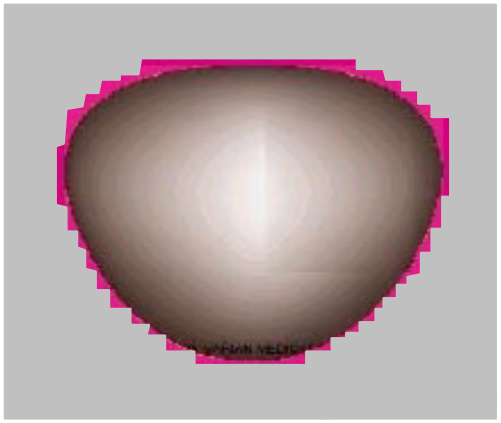


Multileaf Collimation





Automated 3-D Conformal Radiation Therapy

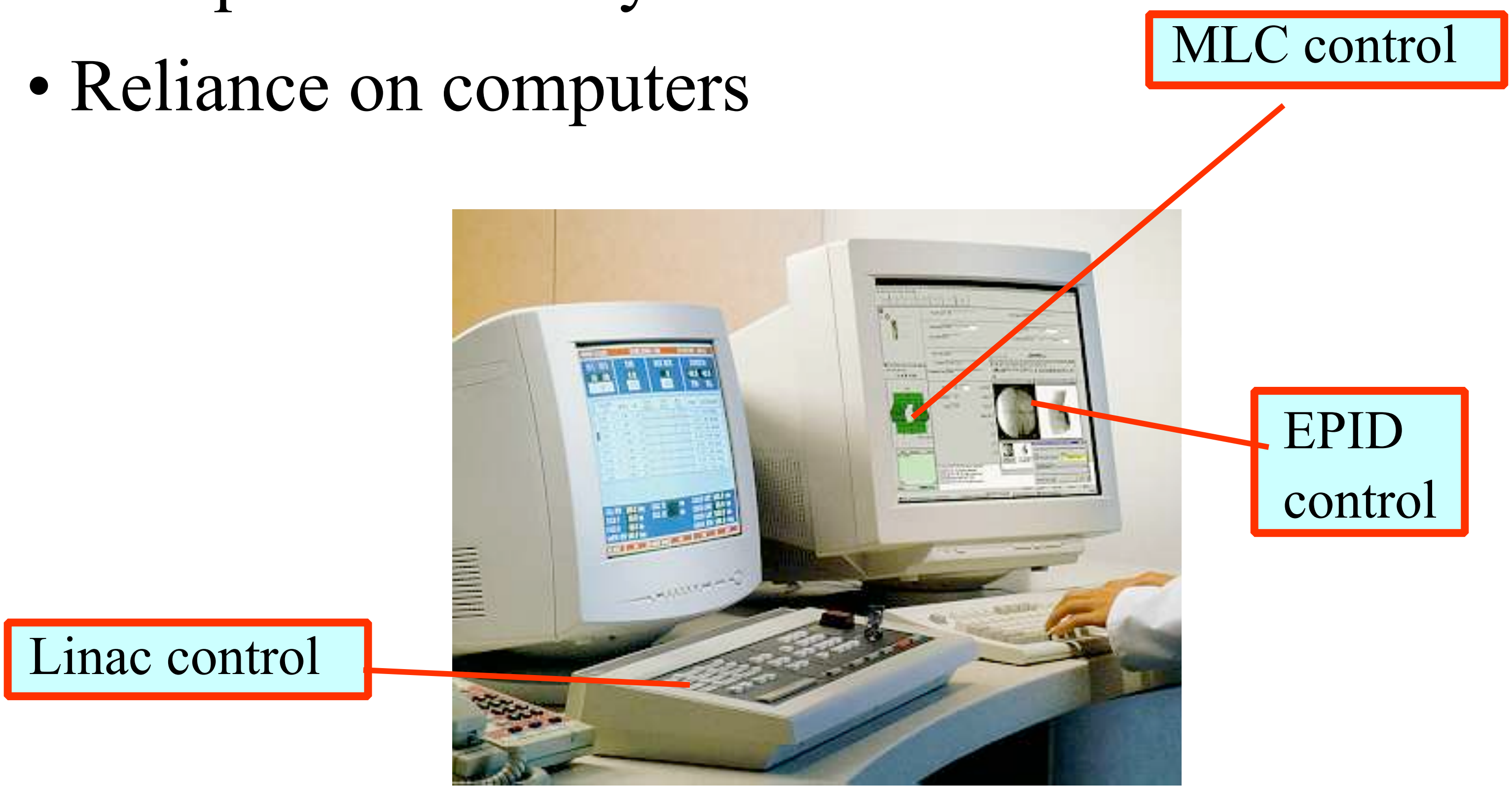


Introduction of the multileaf collimator

- Beam shaping automated with first multileaf collimators (MLC)
- Less labor intensive--no entering and exiting treatment room to change blocks
- Doctors use CT scans to see tumors in 3-D for more precise treatment planning
- Treatment uses 4-6 beam angles

Electronic Accelerators

- Complex control system
- Reliance on computers



Varian Clinac operation screens

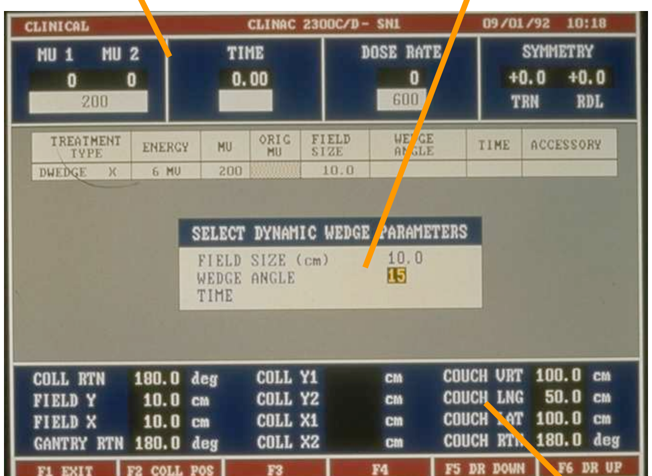
- Clinical mode
- Service mode

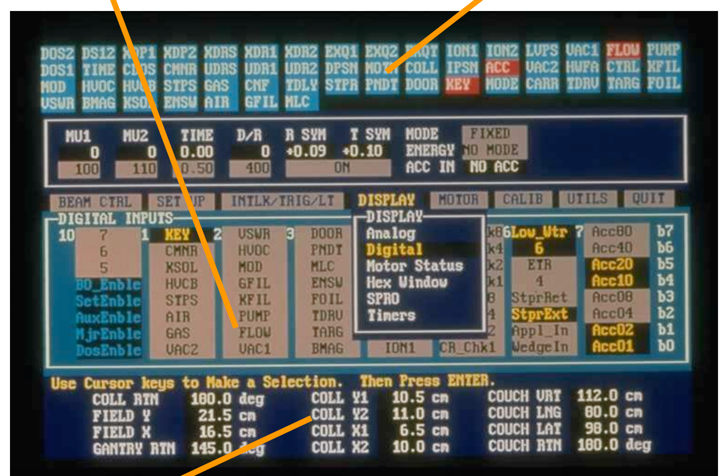
Simple choices

Dose and time

More options

Interlocks





Set-up parameters


PROGRAM
MON 1
MON 2
TIME
MU/MIN
ENERGY
MODE
TECHNIQUE
LATERAL
00.0
LONGIT
+56.2
VERTIC
-53.0
ISOCEN
358.5
ECCEN
269.8
ACCESSORY #1
RETIC
COLLIMATOR
000.0
X JAWS Y
05.0
05.0
G-POS
000.0
ACCESSORY #2
NONE
ACCESSORY #3
NONE
F1 X-FIX
F4 ROT
F5 FILM
F6 SET UP
06-OCT-2004
13:04
45. TREATMENT ROOM DOOR
ViewSonic

Accelerator Operational States

- STAND-BY
  - Working level of vacuum, temp., etc.
  - Possible to move rapidly into operation
- PREPARATORY
  - Set up of essential operating conditions
  - Patient specific (radn. type, energy, gantry angle, etc.)
- READY
  - All conditions set and verified
  - Patient specific
  - Single action to select beam-on
- BEAM-ON
  - Delivering radiation beam
- COMPLETE or INTERLOCK
  - Preset dose delivered or interlock fault is present

Interlocks

- Safety of patient, staff and public
  - Personnel interlocks
    - Radiation, mechanical & electrical hazards
    - Ensure treatment prescription is accurately performed
- Safety of equipment from damage
  - Machine interlocks

Personnel Interlocks

- Dose monitoring & backup
- Dose rate monitoring
- Beam symmetry
- Beam energy or type (electron or photon)
- Beam defining accessories
- Computer control
    - Enforce operator control procedure to minimise possibility of incorrect treatment of patient due to operator error
- Equipment cabinet access doors

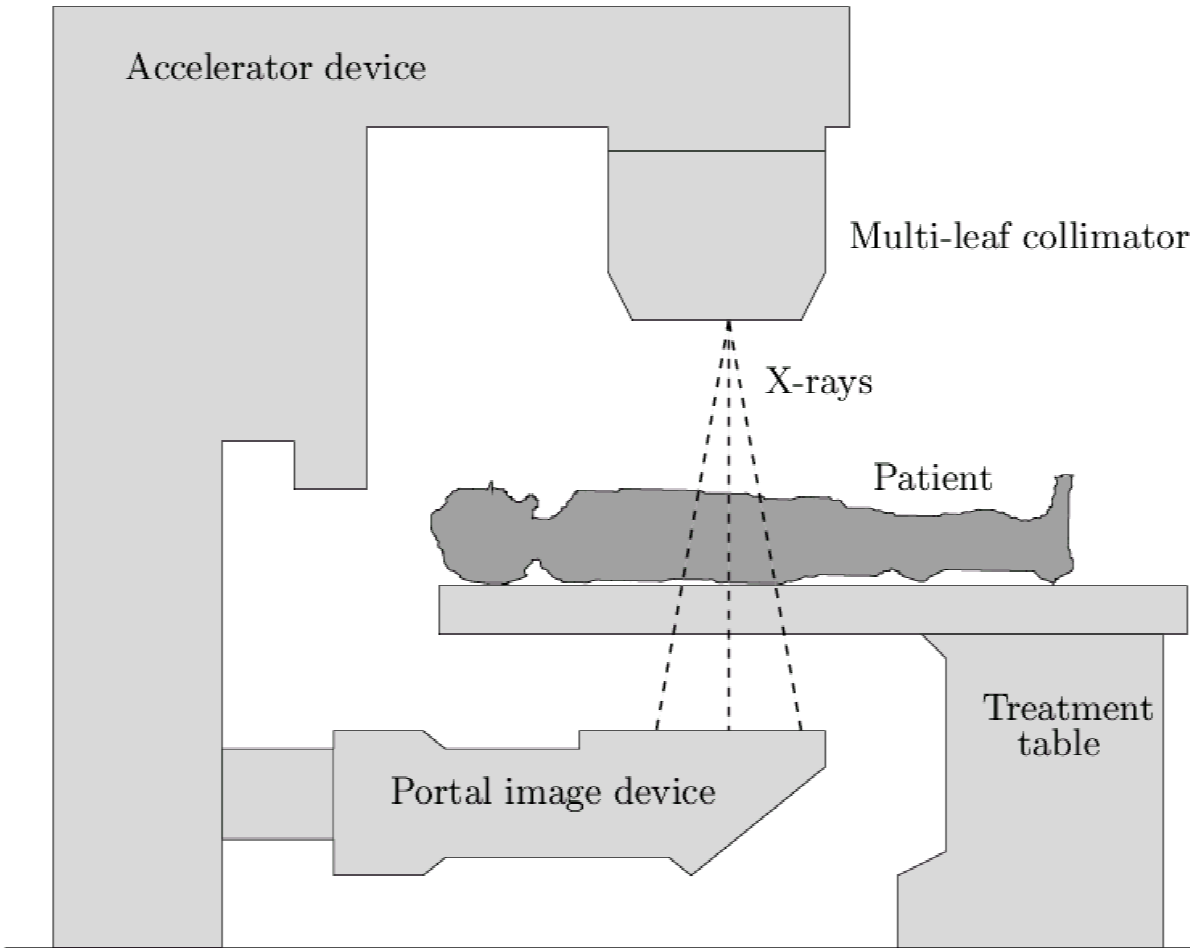
Machine Interlocks

- Modulator malfunctions
- High voltage power supplies
- Accelerator vacuum system
- Guide pressure
- Cooling water flow
- Temperature conditions
- Line voltage excursions

Auxiliary Systems

- Vacuum system
  - Provides extremely low pressures required
  - Electronic ion pump (earlier – oil based rotary pumps requiring lot of maintenance)
- Pressure system
  - SF_6 at 2 bar in the waveguide
- Cooling system & temp. control
  - Temp. controlled water esp. for accelerator which will "detune" with dimension changes due to heat
- AFC
  - To "retune" accelerator by adjusting the operating frequency to optimum (i.e. tuning the klystron or magnetron)
- Monitor & control system
  - Interlocks

Portal Imaging



Electronic Portal Imaging (EPID)

- Imaging device at the beam exit side of the patient to record the treatment field
- Allows to verify that the field was delivered to the correct location in the patient
- Many different systems available...

PortalVision™: Treatment Acquisition

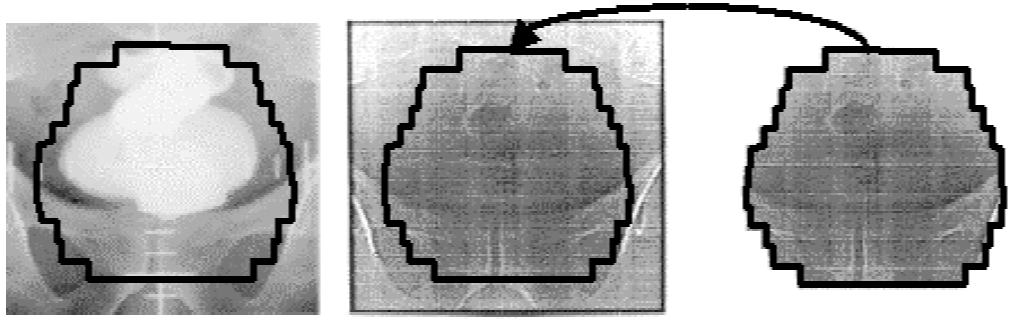
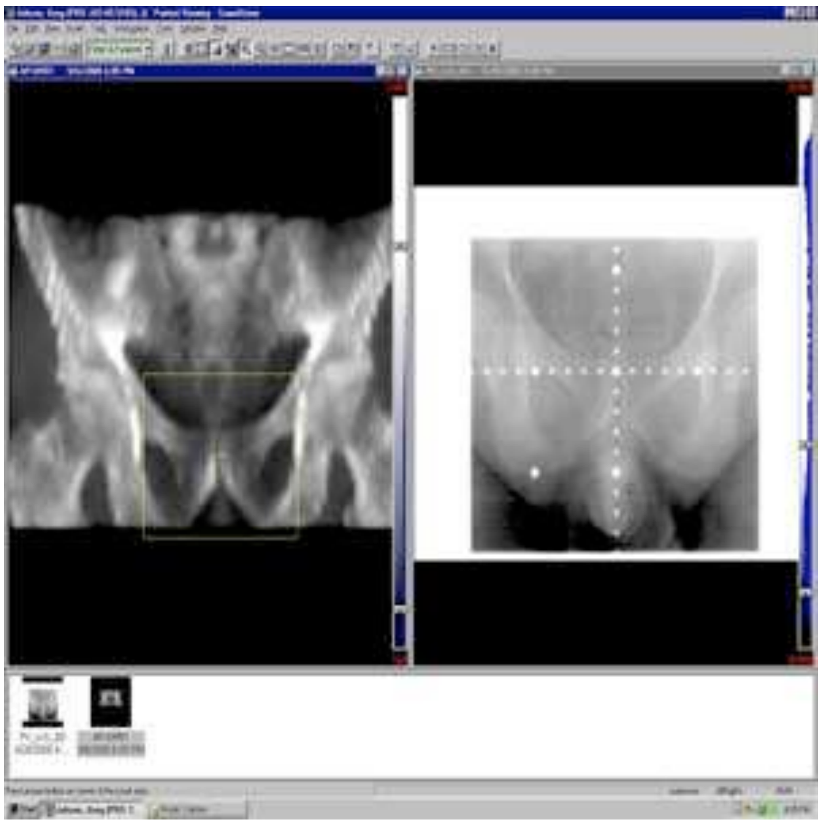


Figure 2 Anatomical images, acquired with the aS500 detector, in comparison with the simulation image (left).



Comparison of simulator and portal image

Record & Verify

- Computer Control
- Verify treatment prescription
- Networked to treatment planning system & treatment machines
- Interlocks treatment machine
- Computer record of treatment given