PRODUCTION OF PARTICULATE AND ELECTROMAGNETIC RADIATION

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BASIC CONCEPTS OF X-RAYS

Three Types of Photon Productions

- Radioactive Decay: γ ray with a fixed energy.
- Characteristic X-ray: knock out an orbital electron to produce characteristic x-ray with a fixed energy.
- Bremsstrahlung

Bremsstrahlung X-ray

- When a high speed electron passes near the nucleus, it suffers a sudden deflection and acceleration due to the attractive Coulomb force between the electron and the nucleus.
- A part or all of the electron energy is dissociated from the electron and propagates as radiation.
- Multiple bremsstrahlung interactions may happen to an electron.
- The resulting bremsstrahlung photon may have any energy up to initial electron energy (not a fixed energy!).

Bremsstrahlung X-ray

- The direction of bremsstrahlung photons depends on the energy of incident electrons
- When e- energy ~ 100 keV, bremsstrahlung x-rays are emitted almost in all directions
- As the e- energy increases, the direction of x-rays becomes increasingly forward
- At MeV e- energy, most photons are in the forward direction
- A transmission target is used in Linear Accelerator

X-ray Energy Spectra

- X-rays are heterogenous in energy
  - A continuous distribution of energies for X-rays + discrete characteristic x-rays
- Filtration effect
  - inherent filtration: remove the low energy x-rays
  - added filtration: enhance the penetration power
- Average X-ray energy
  - 1/3 of the maximum energy

Low Energy Therapy Units

<u>"Grenz-Ray" Therapy</u>

Described as soft or low energy x-rays

X-ray potentials of 20 kV or less

Comparable to mammography energies

No longer used due to extremely low penetration

HVL ≈ 0.04 mm Al

Low Energy Therapy Units

Contact therapy

Operates at potentials of 40-50 kV

Soft component of beam absorbed by .5-1.0 mm thick aluminum filtration

Used with SSD of approximately 2cm

Provides a rapid decrease in depth dose

Incident beam has maximum dose at skin surface and underlying skin is “spared”

HVL ≈ 1.5 mm Al

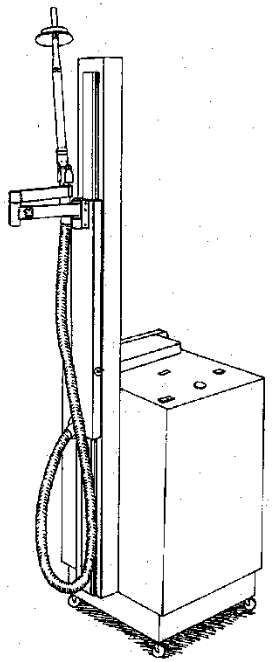


Fig. 15-7 A handheld contact-therapy machine used to treat superficial skin lesions. The operators, one to monitor the patient and the other to hold the applicator, must wear protective shielding during the treatment application.

Low Energy Therapy Units

Superficial therapy

Operating potential of 50-150 kV

Filtration of 1-6 mm aluminum to harden beam

Treatments usually given with cone applicators of 15-20 SSD

Limited to treating tumors of ~ 5 mm depth (90% depth dose)

HVL ≈ 1-8 mm Al

Low Energy Therapy Units

Orthovoltage therapy

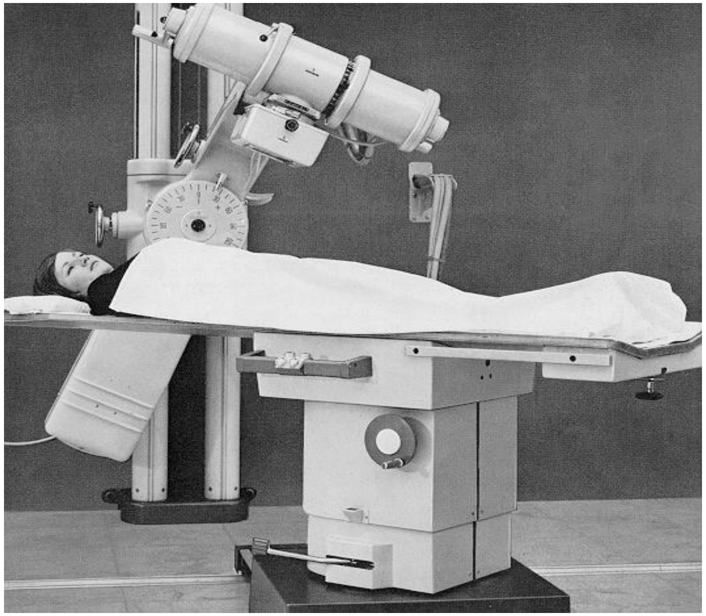
Operating potentials of 150-500 kV

Most equipment operated in ranges of 200-300 kV and 10-20 mA

SSD usually set at 50 cm and has adjustable field size

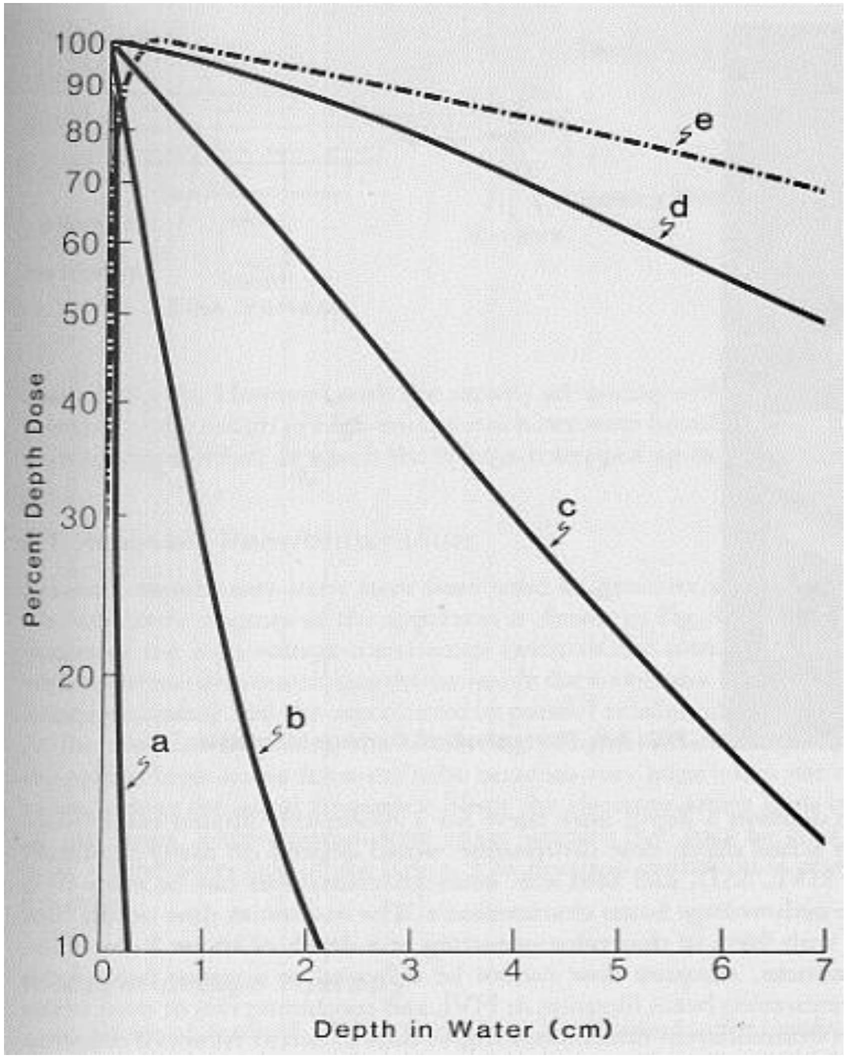
Maximum dose close to surface with 90% dose line at 2 cm depth

HVL ≈ 1-4 mm Cu



Low Energy Therapy Units

Depth Dose Characteristics



a) Grenz rays: 0.04 mm Al
b) Contact therapy: 1.5 mm Al
c) Superficial: 1-8 mm Al
d) Orthovoltage: 1-4 mm Cu
e) ^{60}Co: 1.2 cm Pb

Megavoltage Therapy Units

γ- ray emitters from radionuclides as they undergo radioactive disintegration, include:

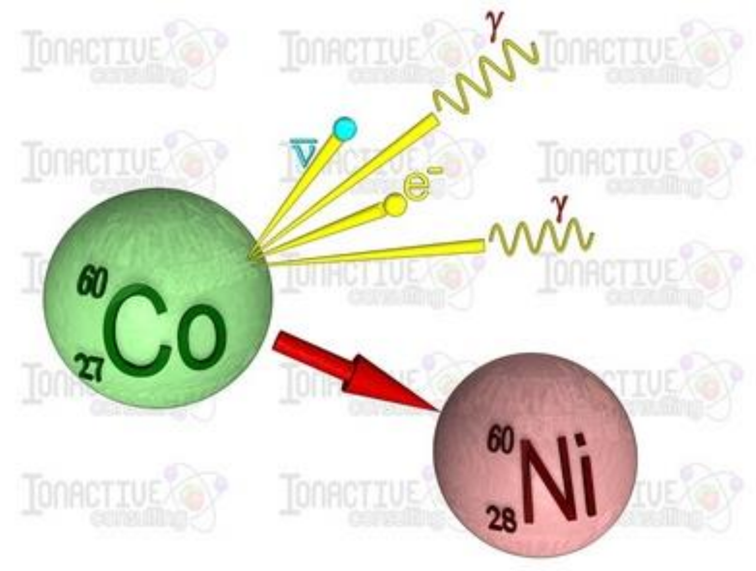
^{226}Ra
^{137}Cs
^{60}Co

^{60}Co most suitable because:

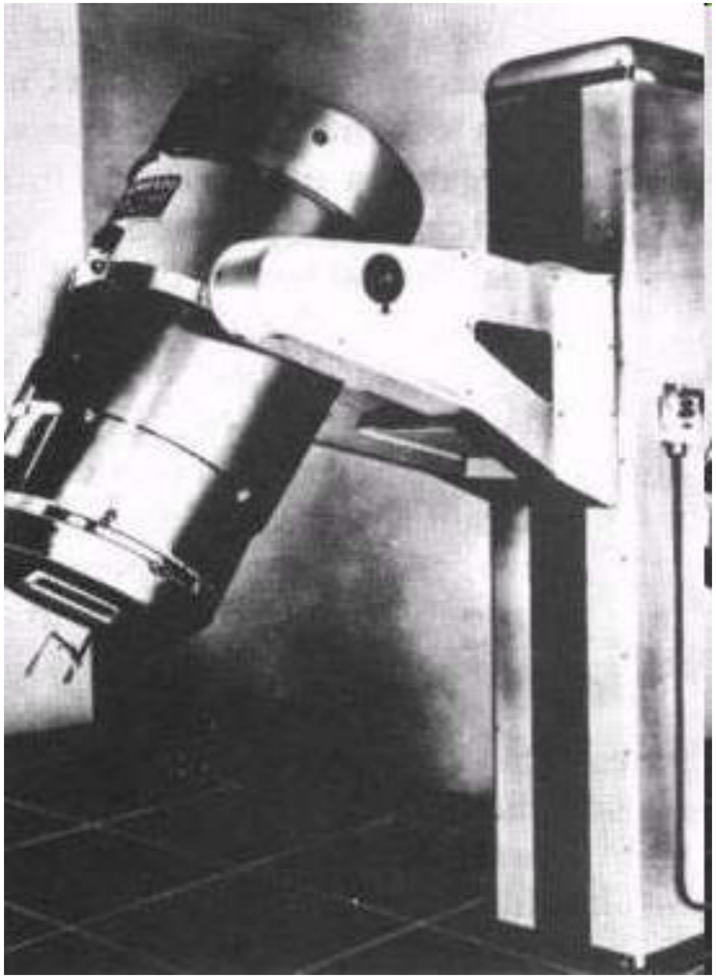
Higher possible specific activity (curies per gram)
Greater radiation output per curie
Higher average photon energy

Cobalt Teletherapy Units

- Produced in nuclear reactor by irradiating stable ^{59}Co with neutrons
- ^{60}Co usually in forms of cylinders, discs or pellets
- A double welded seal prevents β particle leakage (.32 MeV)
- Decays in 5.26 y to stable ^{60}Ni
- Gamma rays of 1.17 & 1.33 MeV used in therapy



Cobalt Teletherapy Units



El Dorado Unit

Theratron Unit

Cobalt Teletherapy Units

Theratron 780

Theratron 1000

Radon Medical, Turkey

Accelerators

- Accelerators are initially built to accelerate charged particles for nuclear and high energy physics research.
- There are two types of accelerators:
  - Straight line accelerators
  - Cyclic accelerators

Straight line	Cyclic
Linac: electrons	Synchrotron: electrons, protons
X-ray tube: electrons	Betatron: electrons
	Cyclotron: Proton, ions, deuterons
	Microtron: electrons

Linear Accelerators

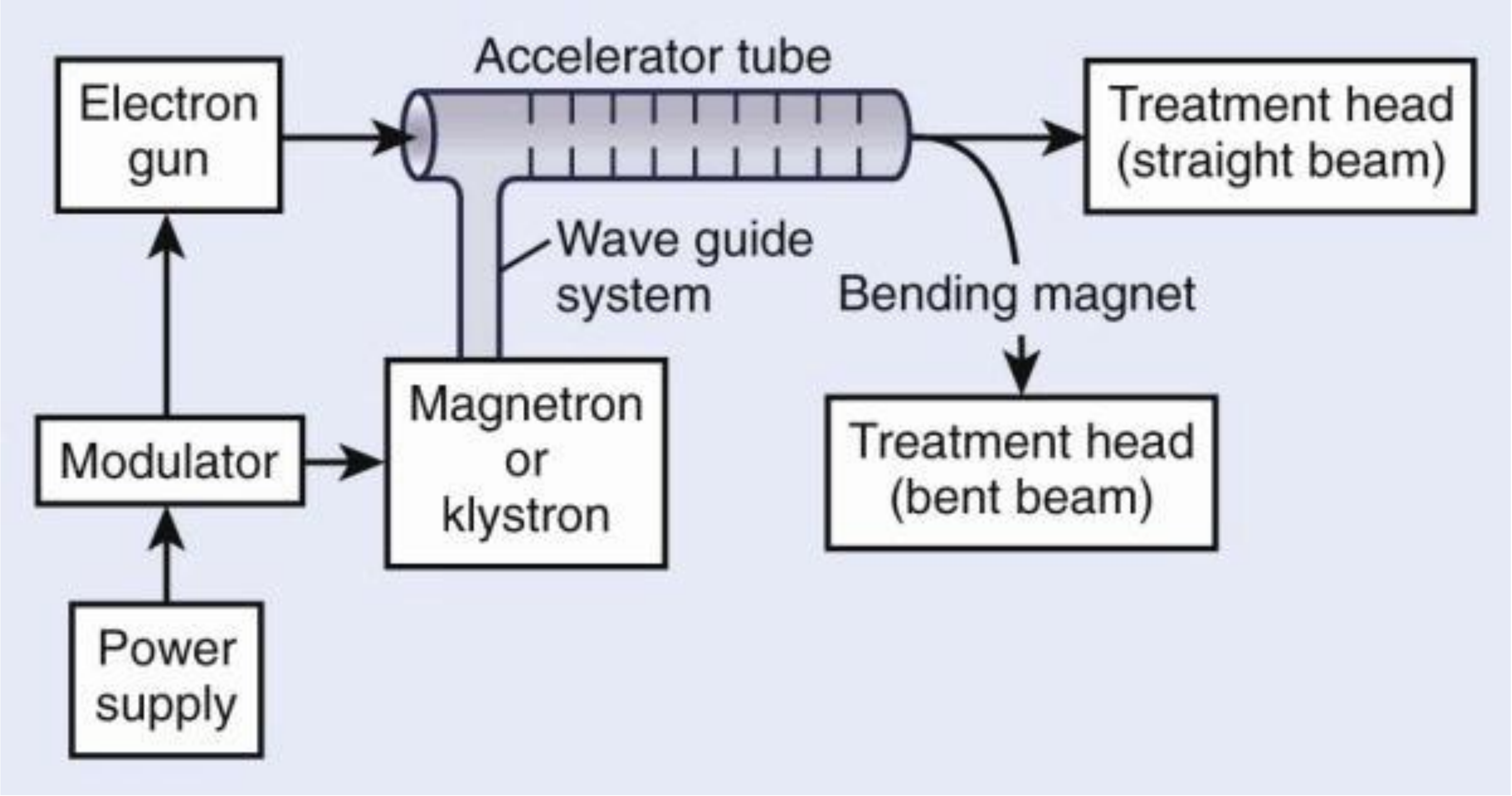
- Medical linear accelerators accelerate electrons with a kinetic energies from 4 to 25 MeV by microwave power source.
- The microwave power source is usually defined as electromagnetic energy ranging from approximately 1 GHz to 100 GHz in frequency.

Linear Accelerators

Five basic Components

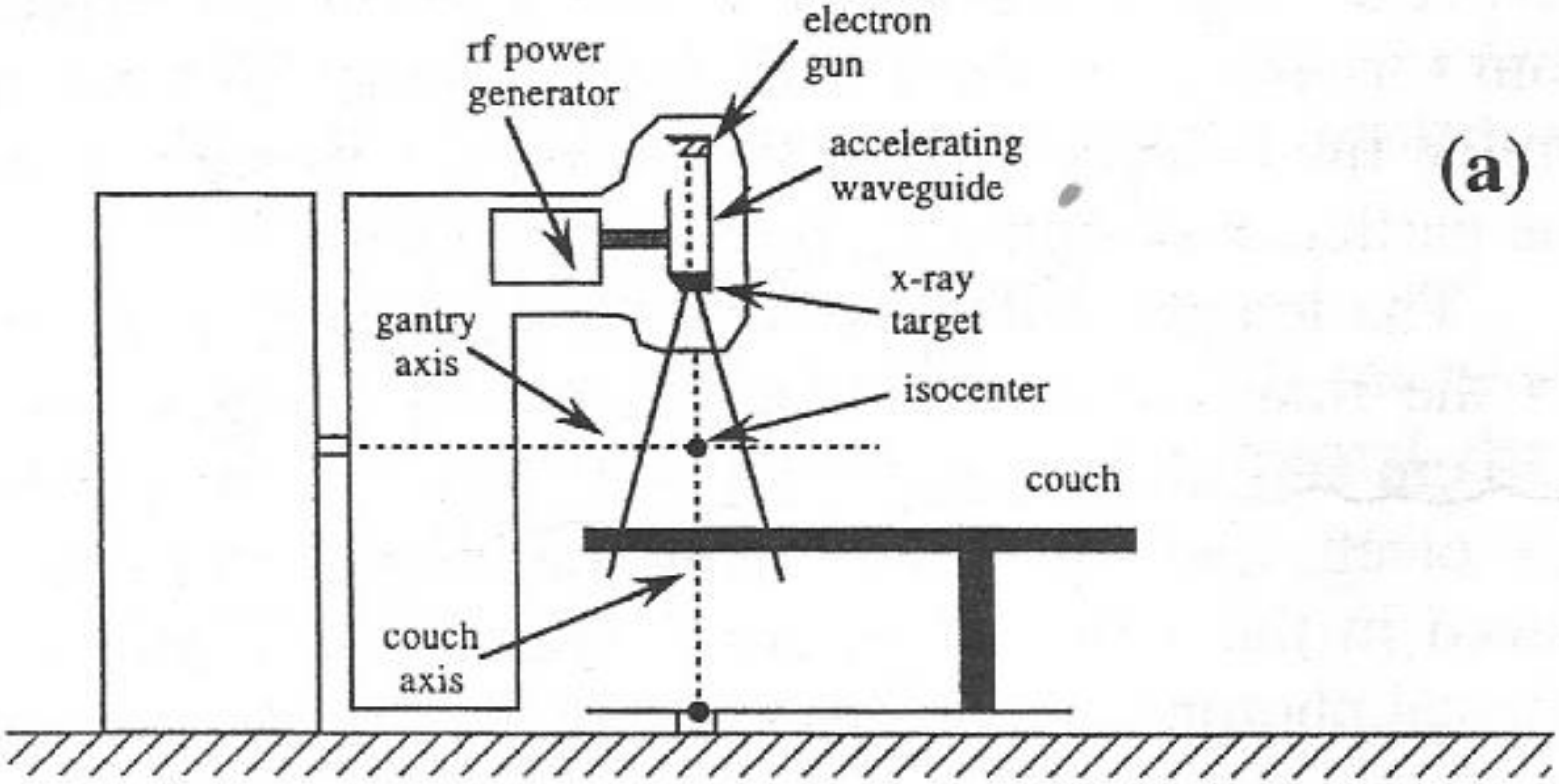
- Injection system – electron source
- RF system- magnetron/klystron, modulator, modulator control unit, waveguide & circulator
- Auxiliary system – vacuum pumping system (waveguide), water cooling system, gas dielectric system for transmitting microwaves from RF generator to accelerating waveguide.
- Beam transport system – target/scattering foil, magnetic steering, focusing
- Beam collimation & monitoring system – shaping, monitoring of beams

Linear Accelerator

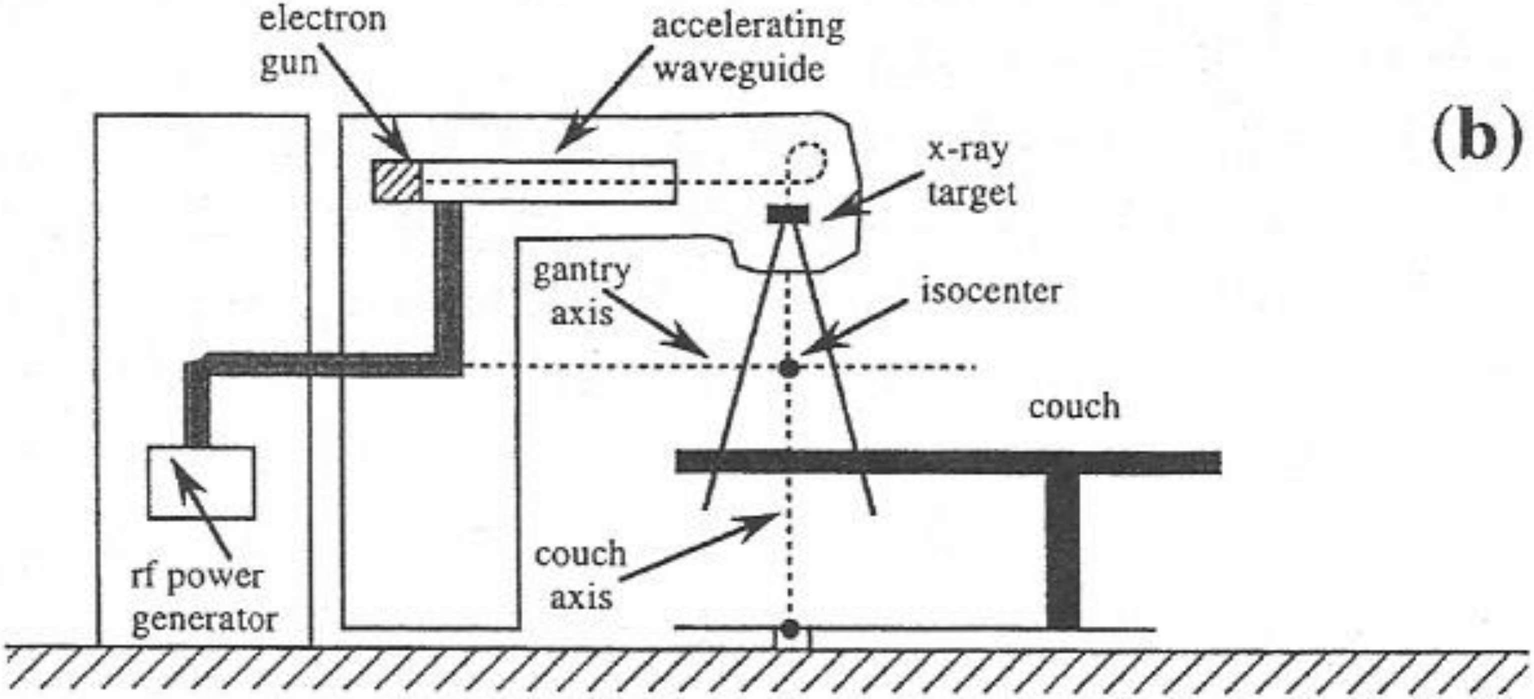


A block diagram of Linear accelerator

Simple LINAC



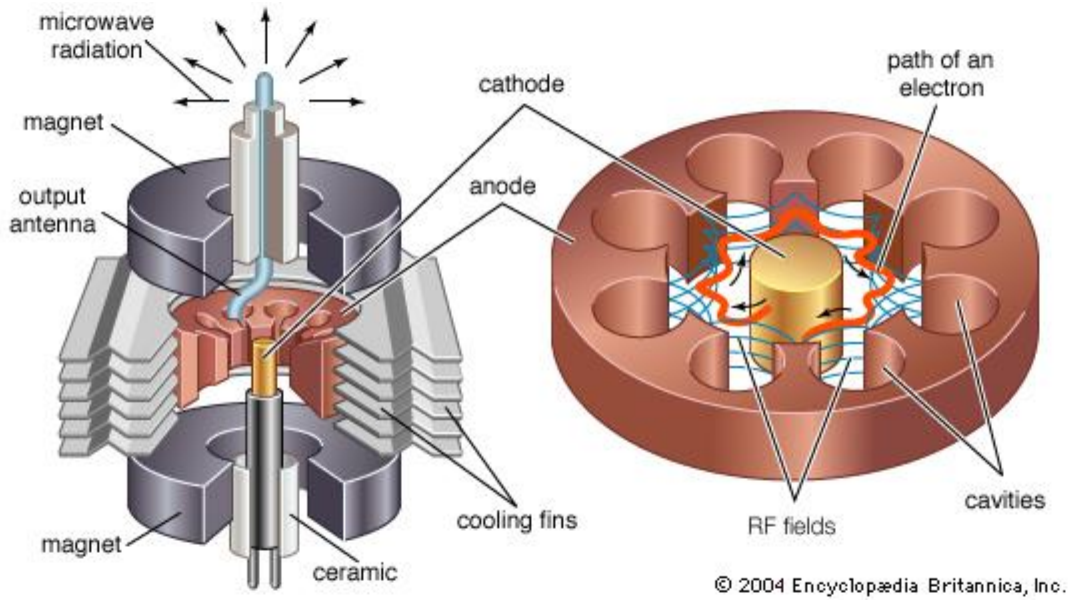
Modern LINAC



Microwave Generators

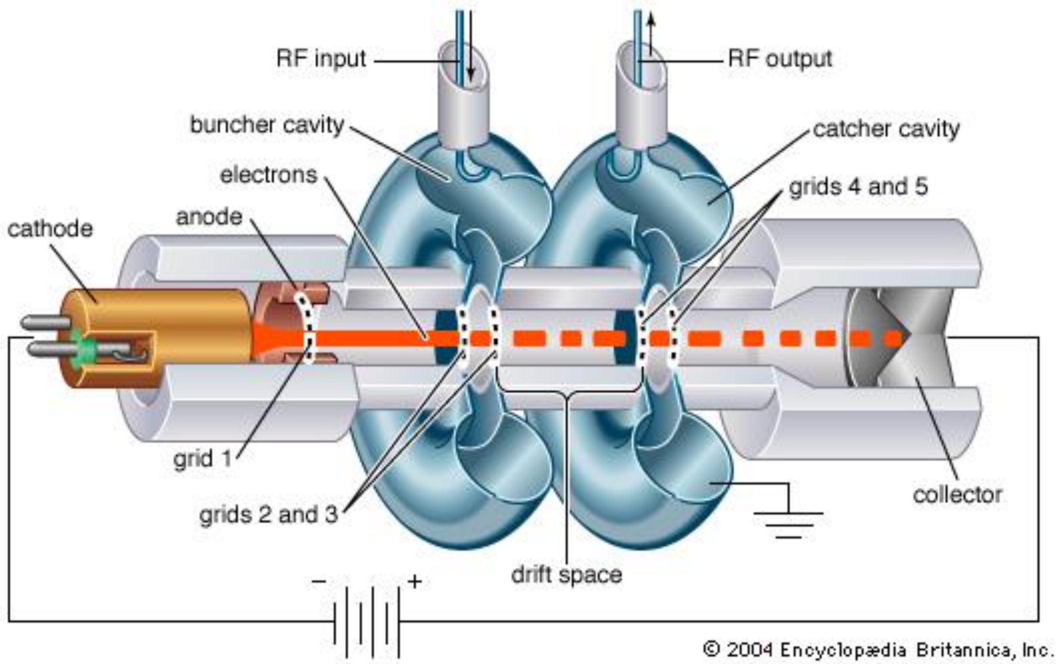
- Magnetron and Klystron are two typical microwave generators normally used in Linear accelerators
- Magnetron:
  - Supply 2 MW peak power, more compact, and inexpensive
  - Can be mounted in the Gantry
- Klystron:
  - Supply higher peak power (5 MW), bulky, and more expensive
  - require a low RF power as input, Usually installed in or behind the gantry stand

Magnetron



- Electrons spiral outward from cathode in vacuum.
- Induce high power RF fields in cavities.
- Converts up to 60% to microwave power, extracted with an output antenna.
- High heat limits microwave power.

Klystron



- Electrons are accelerated/decelerated by oscillating RF field across buncher cavity, causing bunching of electrons.
- Catcher cavity (same resonant frequency as buncher cavity) is excited by electrons and create high power RF field in catcher cavity.
- Bremmstrahlung created as a result of collision with collector.

Magnetron vs. Klystron:

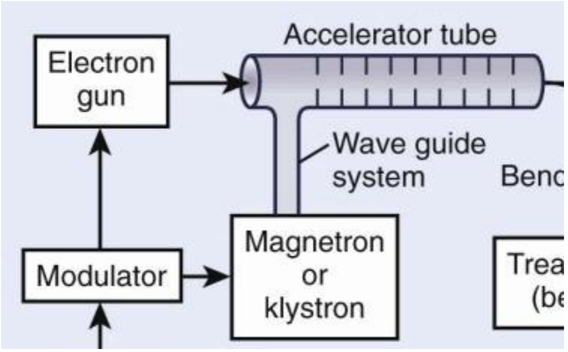
- Magnetron is smaller
- Magnetron does not require input RF signals
- Klystron mounted within a tank of insulating oil (has to be stationary, cannot be within rotating gantry).
- Magnetron less stable.

Klystron:

- Klystron needs to produce MW power – not possible to continuously operate.
- Operates at a duty cycle (fractional on-time) of 10^{-3} to 10^{-4}.
- Average power KW, instantaneous power MW.

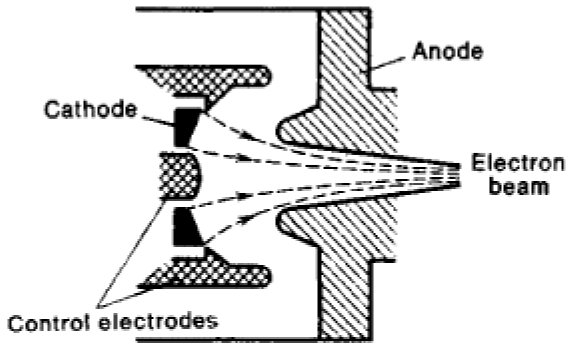
What Is a Waveguide?

- A waveguide is gas filled (if only used for EM waves) or evacuated (if EM + electron acceleration) metallic structure of rectangular or circular cross section
- Gas filled waveguide from Klystron/Mangetron transmits microwave RF source into accelerating waveguide.
- Inside the evacuated accelerating waveguide, electrons are accelerated to a near light speed.



Pulsed modulator

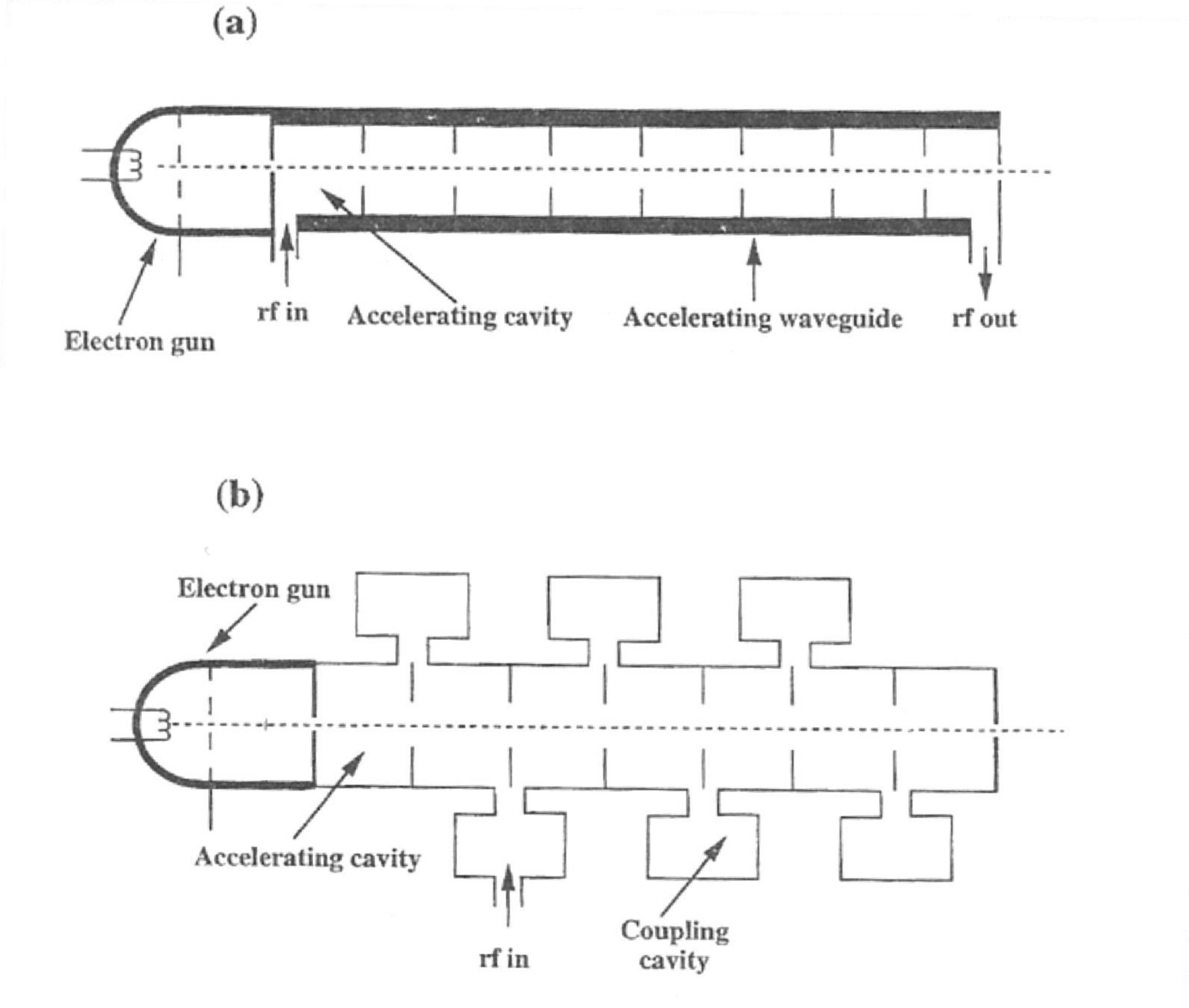
- Housed in the linear accelerator vault.
- Pulse lengths of a few μs (~1000 pulses per second)
- Pulse transformer is used to amplify voltage
- Pulses sent to the cathode of Klystron/Magnetron as well as cathode of electron gun.



electron gun

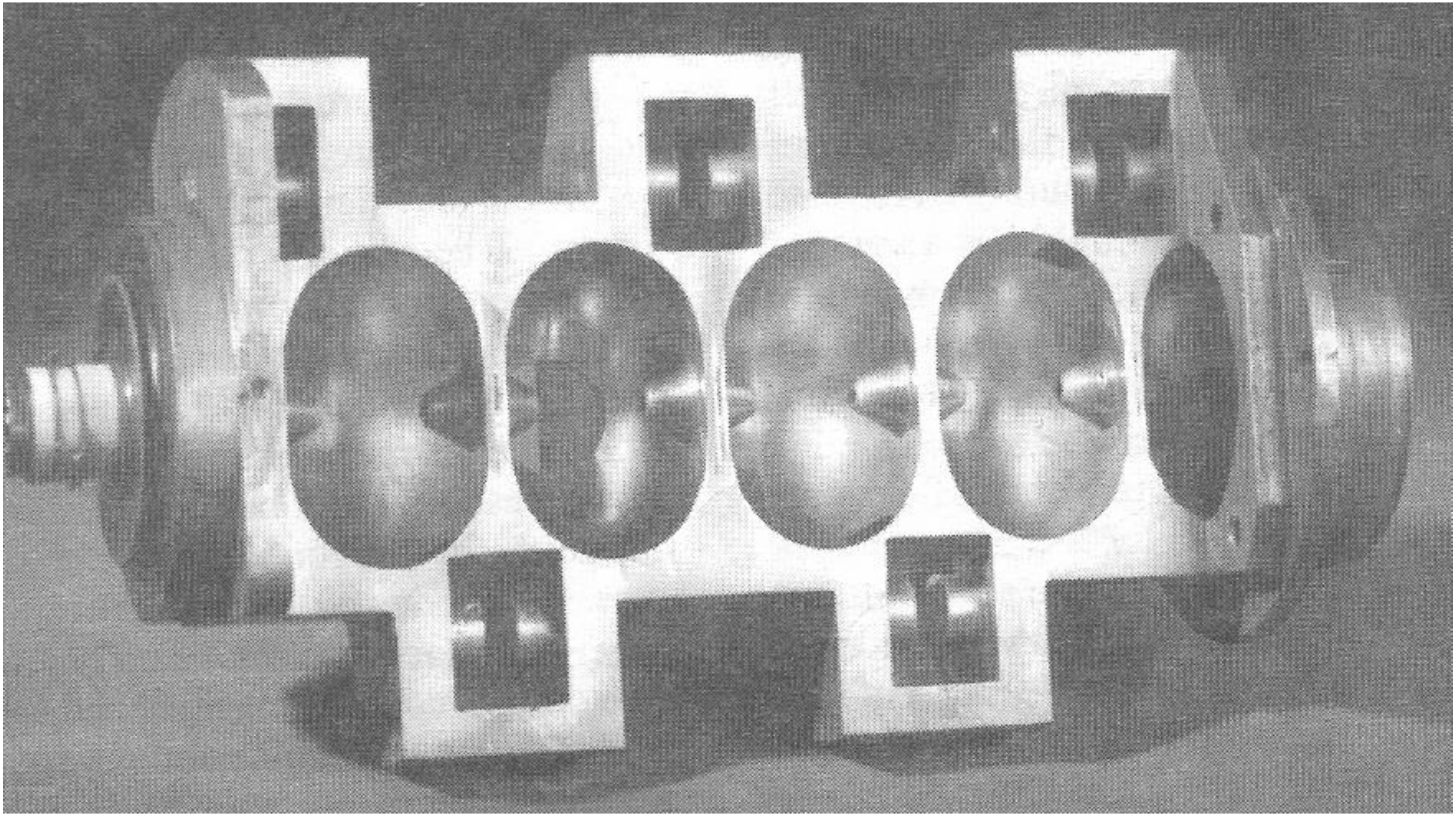
Wave and Particle Duality

- Waveguide theory is an example of how particle (electrons) and electromagnetic field (Microwave) exchange energy.
- The propagation of microwaves through a uniform waveguide is governed by Maxwell's equations and boundary conditions.


(a)
Electron gun
rf in
Accelerating cavity
Accelerating waveguide
rf out
(b)
Electron gun
Accelerating cavity
rf in
Coupling cavity

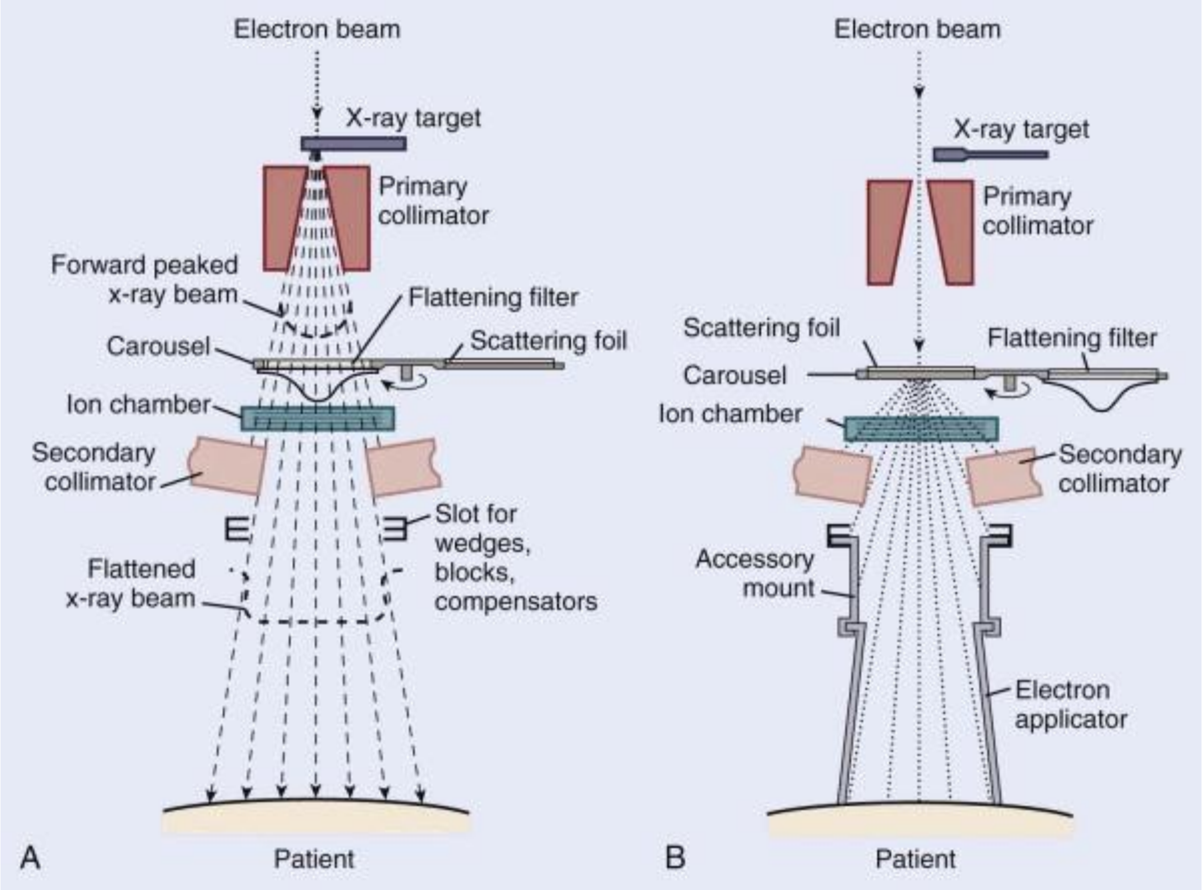
Traveling and Standing Wave-guides

- Traveling wave-guide:
  - The residual power is absorbed by a dummy load
  - No reflected wave
- Standing wave-guide:
  - A special devise (isolator/circulator) to deal with unwanted reflected power going back into Klystron.
  - Shorter wave-guide can be used to achieve the same electron energy as the traveling waveguide.
  - Requires 25% greater RF power



Beam Delivery

- Bending Magnet
- Target
- Fixed (primary collimator)
- Flattening filter
- Monitor ionization chambers
  - Transmission type
- Movable collimators and Multi-leaf collimators

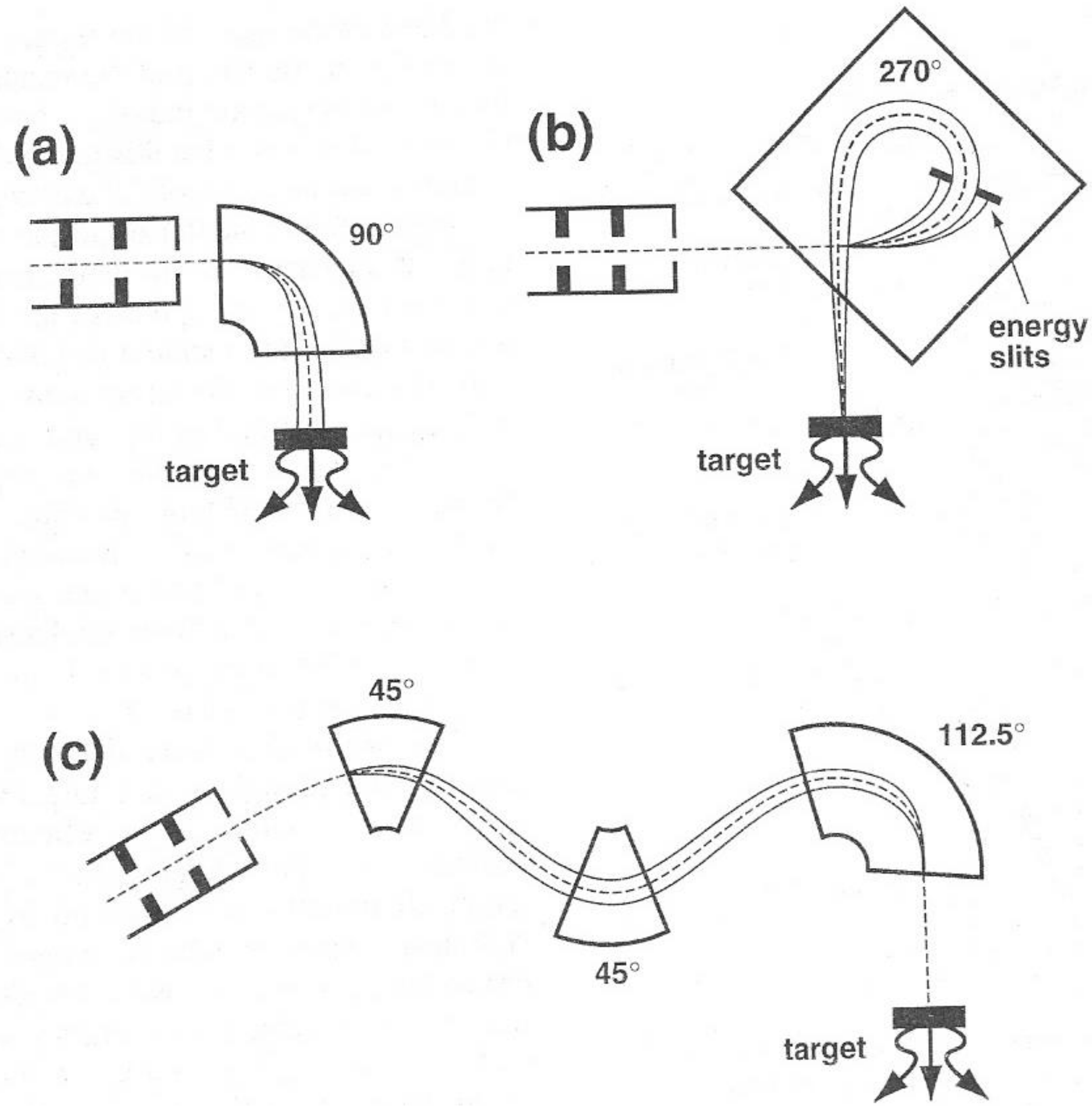


Electron beam
X-ray target
Primary collimator
Forward peaked x-ray beam
Flattening filter
Carousel
Scattering foil
Ion chamber
Secondary collimator
Slot for wedges, blocks, compensators
Flattened x-ray beam
Patient
A
Electron beam
X-ray target
Primary collimator
Scattering foil
Flattening filter
Carousel
Ion chamber
Secondary collimator
Accessory mount
Electron applicator
Patient
B

Bending magnet

- For energies > 6 MV, waveguide is too long and must be placed horizontal, so beam has to be bent.
- 90 °, 270 °, 112.5 ° bending magnet.
  - ➢ 90° magnet – acts as a spectrometer that bends higher energies less, so large focal spot;
  - ➢ 270 ° magnet – refocuses spectral spread to provide a small focal spot, but bulky (height);
  - ➢ 112.5 ° magnet – advantages of small space with small focal spot.

Electron Transport System



Target

Electrons strike target to create: (1) collisional losses; (2) radiative losses; (3) scattering.

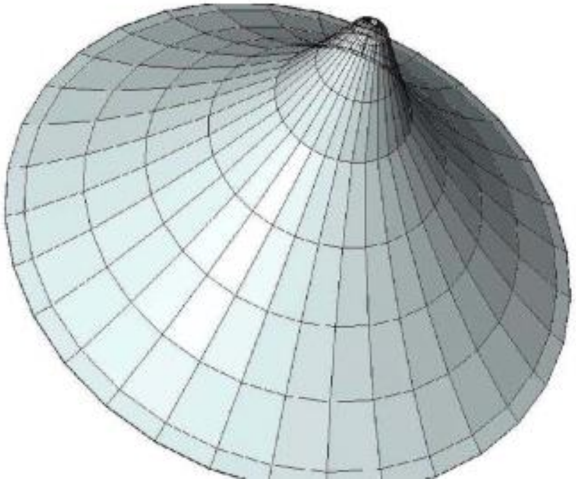
- Collisional losses result in heat – dissipated using circulating chilled water.
- Radiative losses produce photons that are in the same direction as the incident electrons.
- Scattering of electrons in the target result in angular spread of the resulting radiation. The higher the target atomic number, the higher the scattering.

Target selection:

- Intermediate to low Z targets produce higher photon yield, but need to be thicker to absorb all electrons (e.g., lead 10mm, tungsten 5 mm, aluminum 5 cm – too thick to accommodate in head).
- Copper is intermediate Z and suitable.

Flattening filter

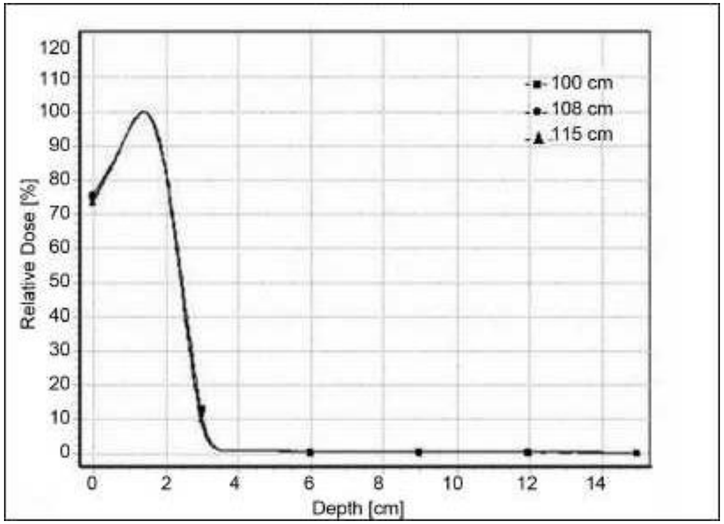
- Flattening filter converts the gaussian shaped field profile into a “flat” beam profile
- 40 x 40 field (100 SSD) at 10 cm depth should have dose variation within the central 80% of field not more than ±3% of central axis value.
- Increased hardening in central portion results in “horns” at depths less than 10 cm (horns at dmax ± 6%)



Clinical electron beams

- Target and flattening filter are moved out.
- Beam output is a pencil beam with gaussian profile – cross sectional area too small for clinical use.
- Scattering foil on rotating carrousel is used to broaden beam. Thin foil of high Z material, e.g., copper or lead.
  - Thin to prevent secondary photons.
  - Resulting beam is still gaussian, but broader.
- Electron applicator, in conjunction with jaw position is used to further flatten beam.

- Secondary photons are caused by interaction of electrons with scattering foil, ion chamber, jaws and electron applicator.
- Scattering foil, ion chamber and applicator should be as low Z as possible to reduce X-ray contamination. X-ray contamination can range from 1% for 6 MeV to 5% for 25 MeV.



Relative Dose [%]
Depth [cm]
100 cm
108 cm
115 cm
0
10
20
30
40
50
60
70
80
90
100
110
120
0
2
4
6
8
10
12
14

Multi-leaf Collimator Designs

- Each manufacturer has a different design of MLC
  - Location, leaf width, and leaf end design
  - Single focused or double focused
  - Restrictions on motion (path, over-travel, interleaf)
  - Field size
- These factors have an impact on IMRT delivery and must be considered in treatment planning

Double Focused MLC

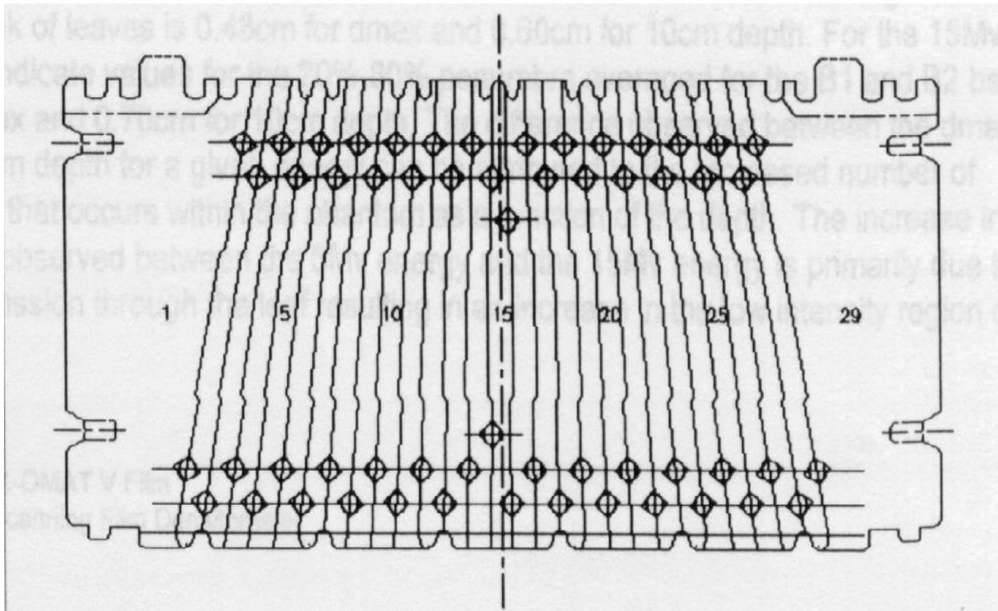
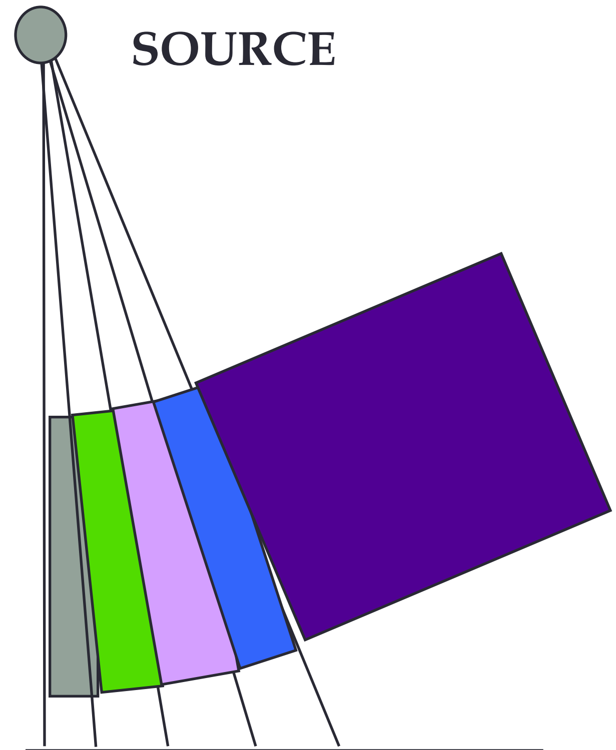


Figure 2. Cross section of leaf bank geometry



Focused in in-plane (Y)

Focused in cross plane (X)

Single Focused MLC

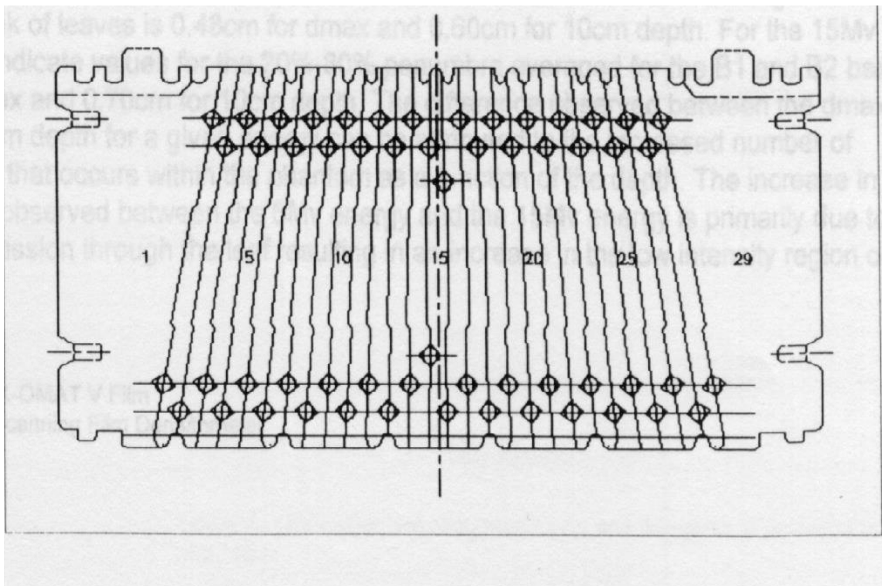
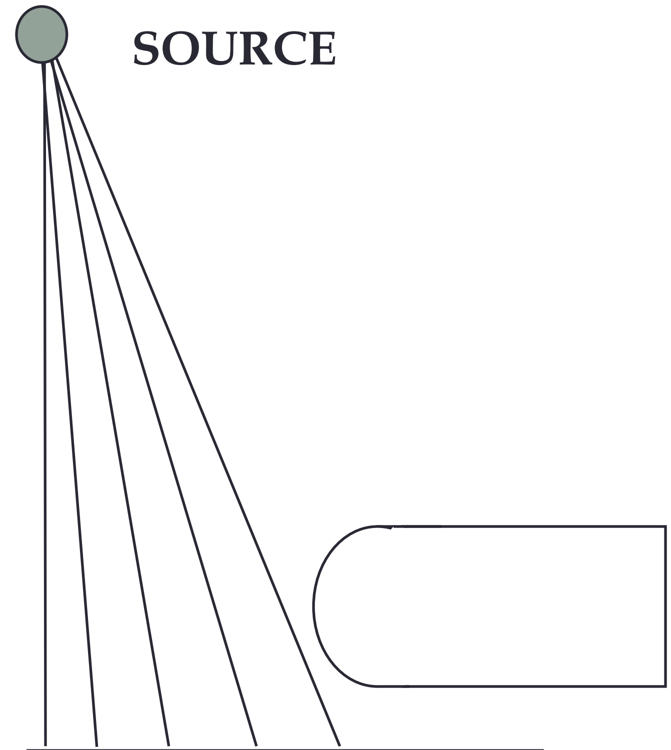


Figure 2. Cross section of leaf bank geometry

Focused in in-plane (Y)



Focused in cross-plane (X)

Beam Collimation and Penumbra

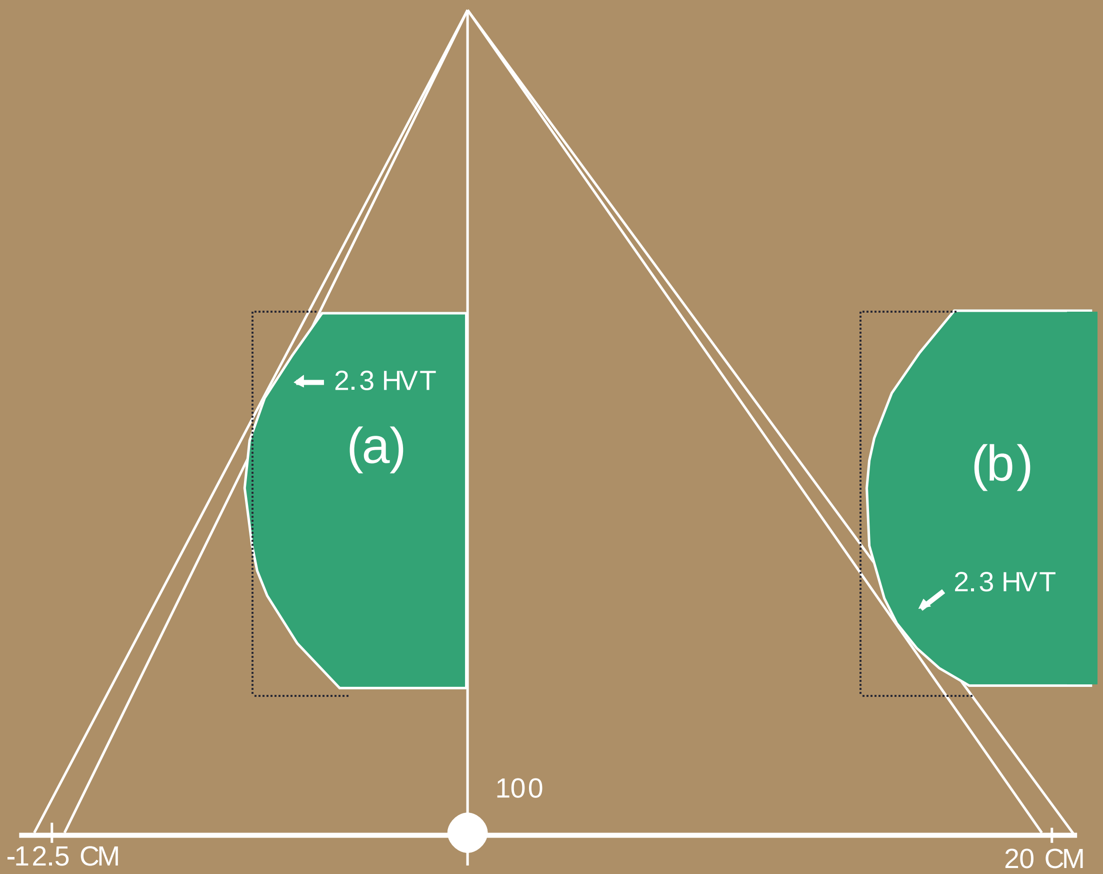
- Transmission Penumbra
  - The inner surface of the collimator is parallel to the CAX
- Geometric Penumbra
  - Due to the finite radiation source , s

$$P_d = s\,(SSD + d - SDD)/SDD$$

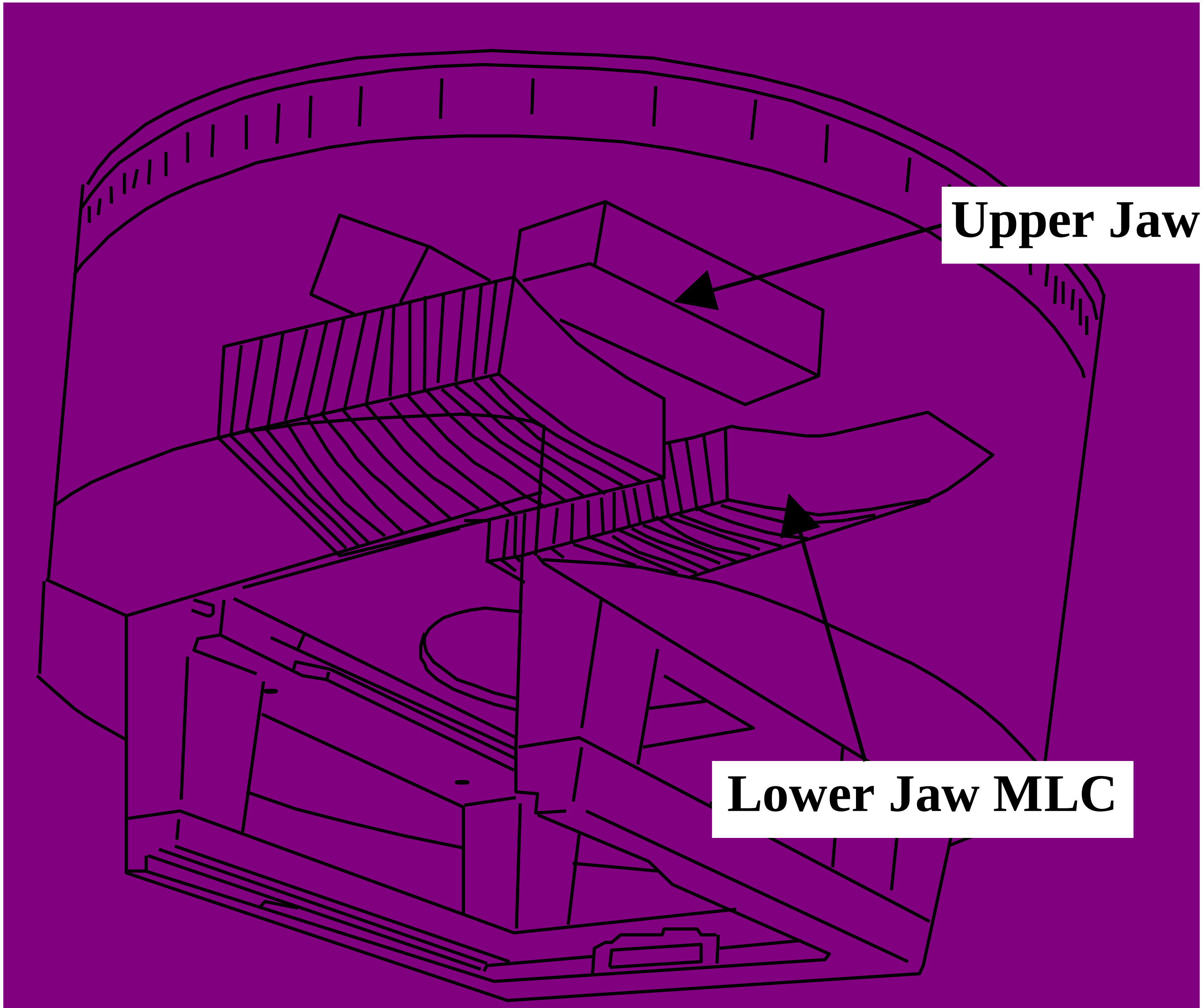
Where SDD is the source to diaphragm distance

- Physical Penumbra
  - define the distance between the 20%-90% IDL

Rounded Leaf End vs Penumbra



Siemens MLC

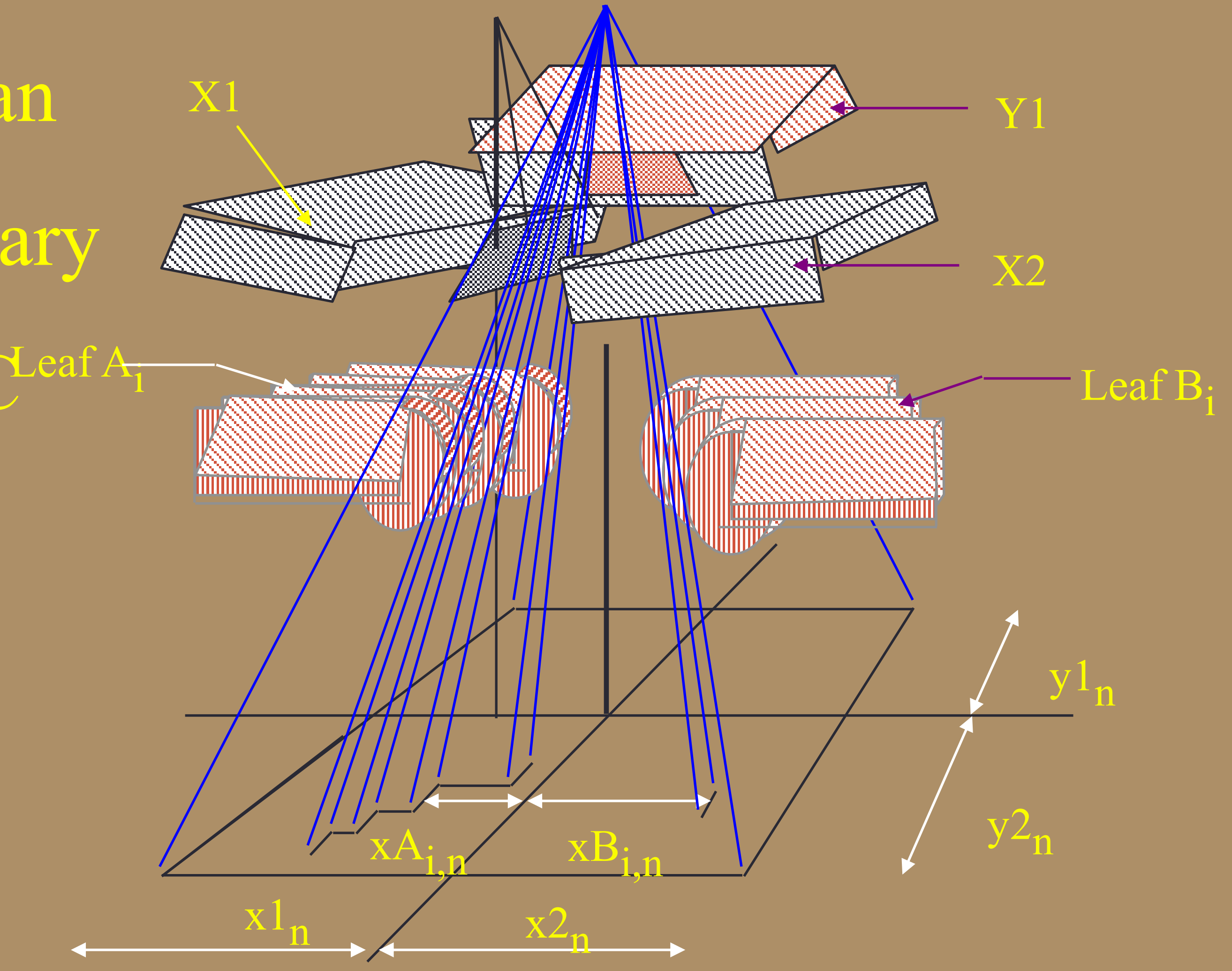


Varian MLC System

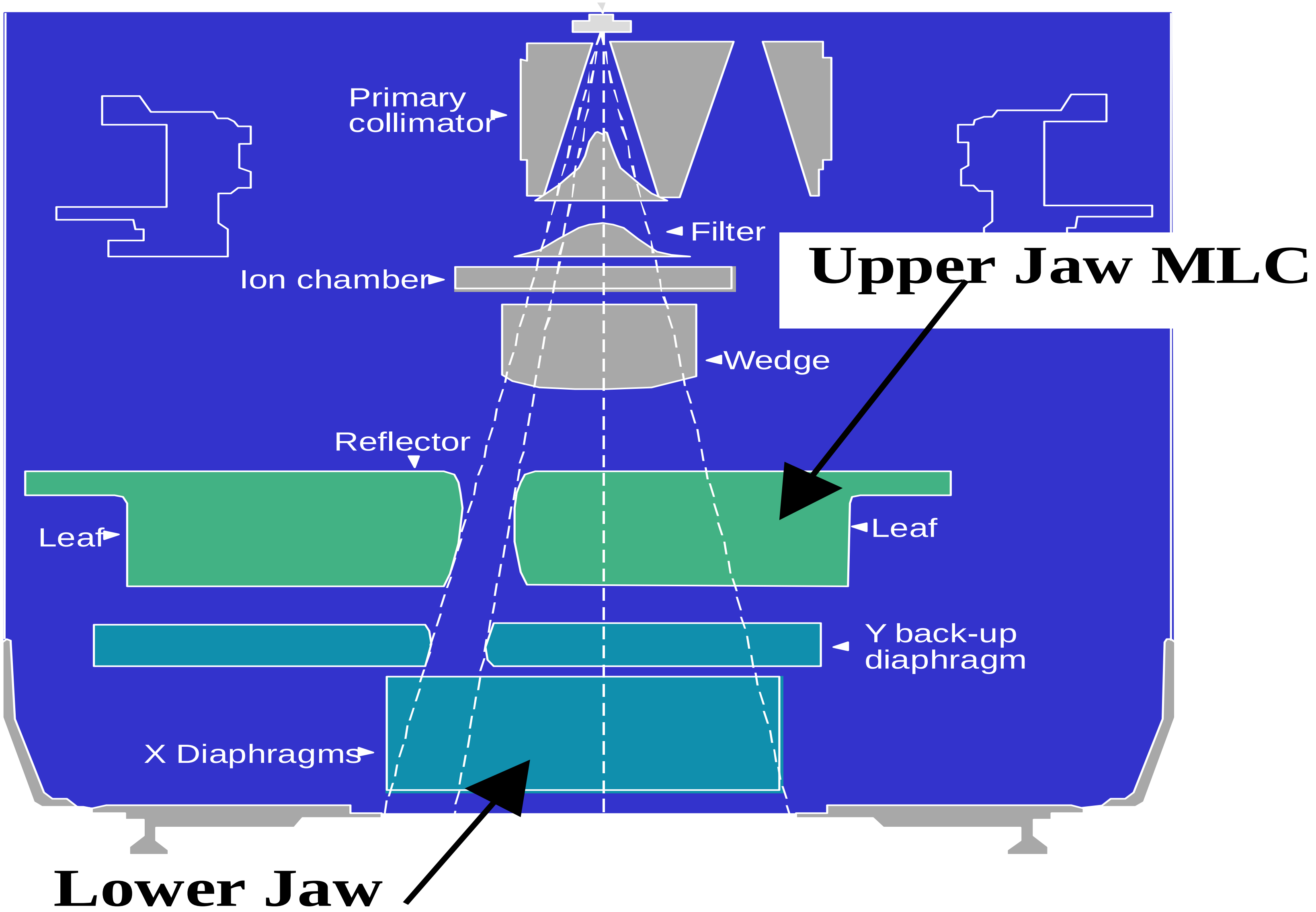
Varian

Tertiary

MLC



Elekta MLC System



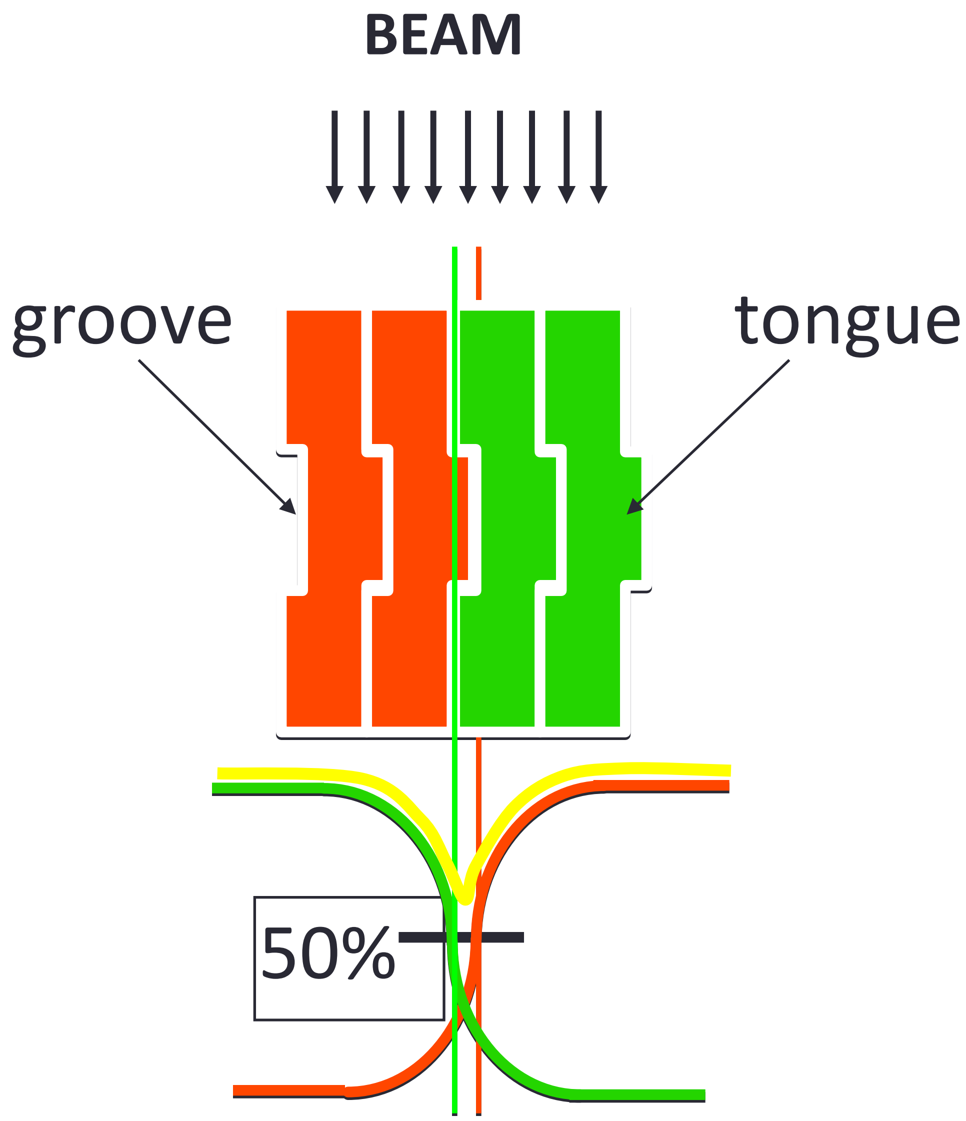
Physical Leaf Length vs. Over-travel Distance

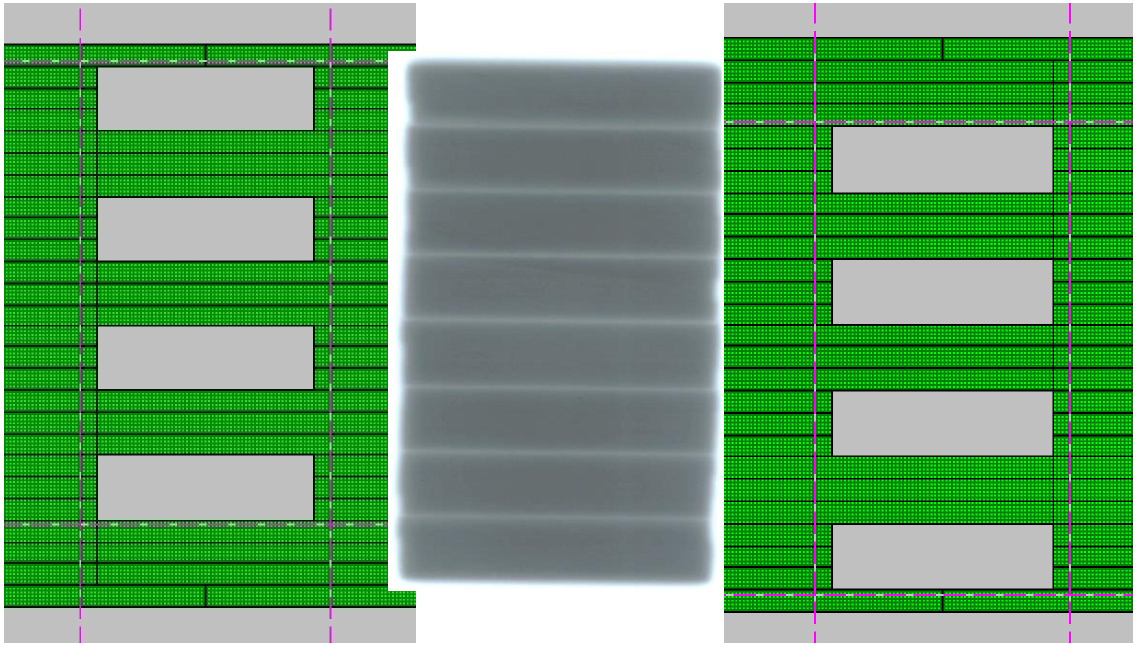
- The MLC physics leaf length (project to iso-center) is 16 cm, 30 cm, 32.5 cm for Varian, Siemens, and Elekta Accelerators, respectively.
- The distance that each individual leaf passes over iso-center is called over-travel distance, without leaving an uncovered region behind the leaf.

Over-travel Distances

- For Siemens and Elekta machines, the over-travel distances are 10 cm and 12.5 cm, respectively, without leaving a uncovered region behind the leaf.
- For Varian MLC, X jaw is used to cover the uncovered region of MLCs. The over-travel distance = 2 cm (x jaw over-travel distance) + 15 cm = 17 cm.
- The maximum differences between the leading leaf and the trailing leaf $\leq$15 cm

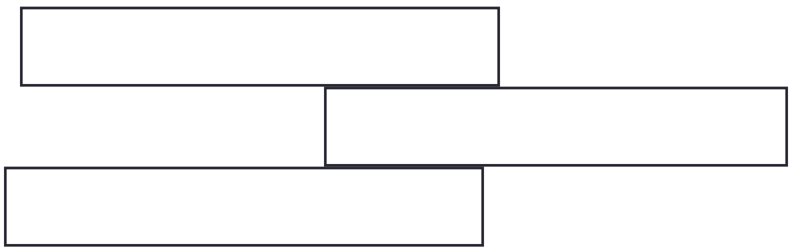
Tongue & Groove



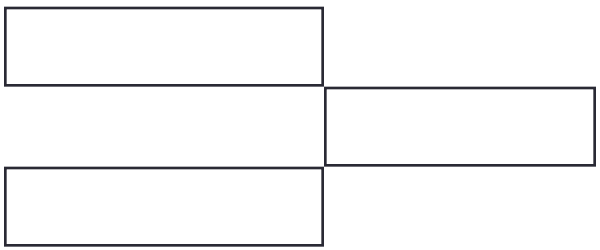


a b c

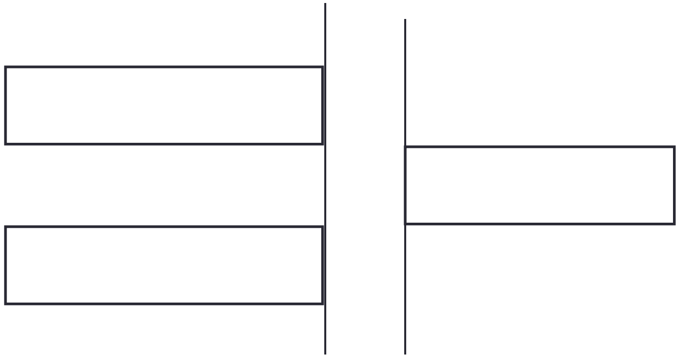
Leaf Motion Constraints



Interdigitation (Varian)



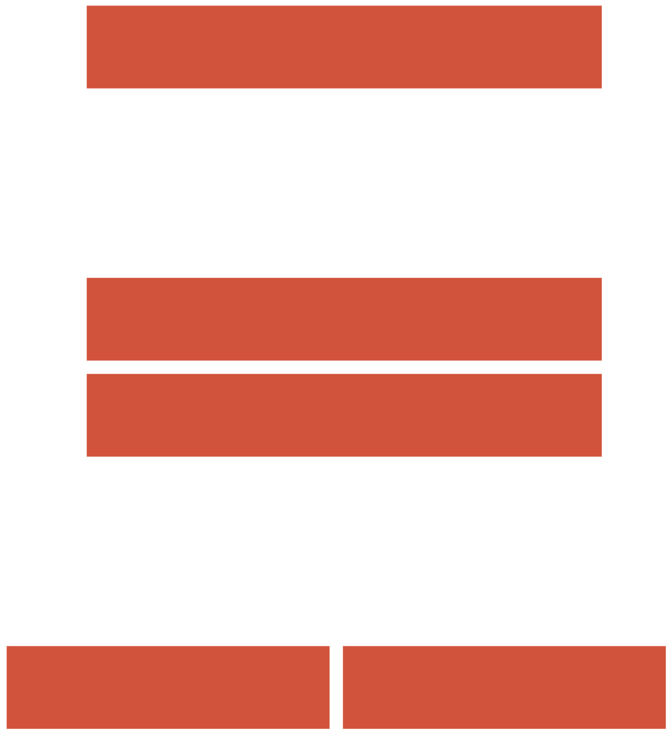
No interdigitation (Siemens)



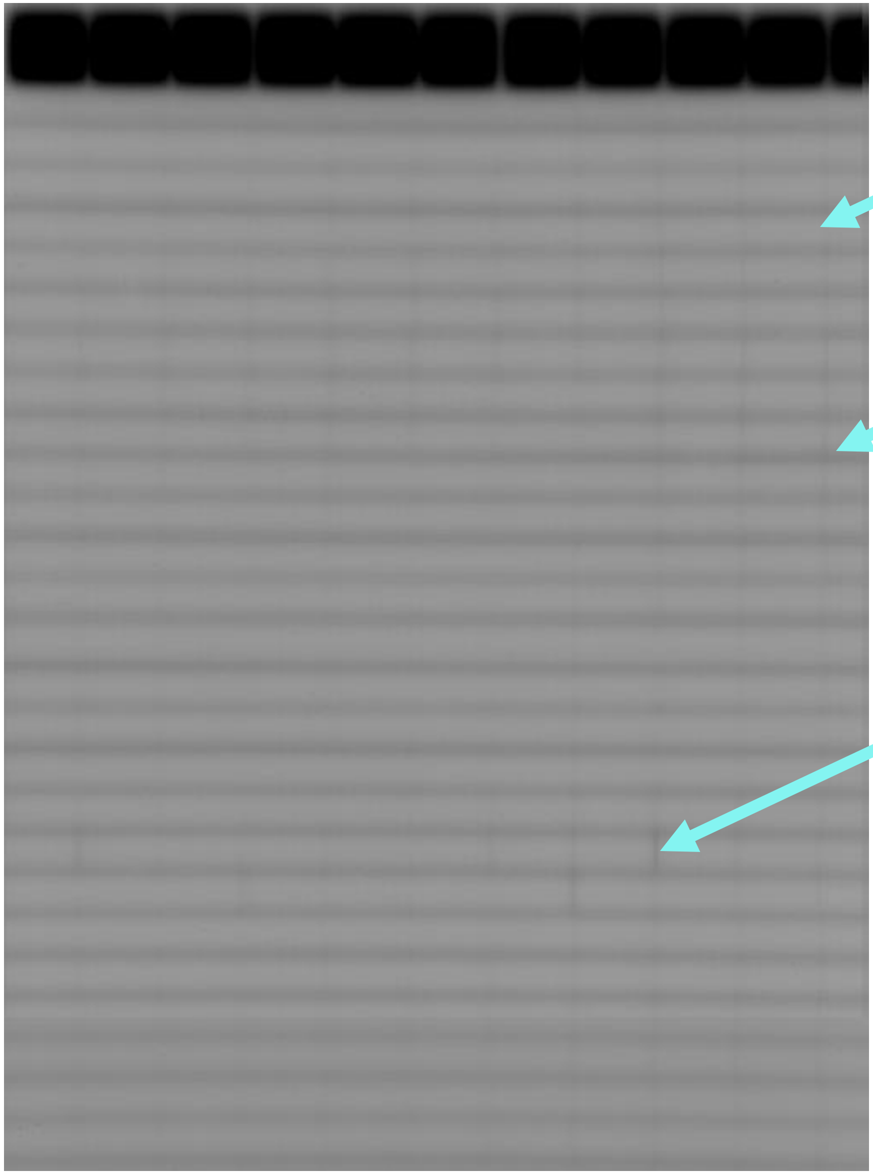
Minimum Gap (Elekta)

Segmentation is affected by these constraints

MLC Leakages



- Intra-leaf leakage
    - Thickness (1-2%)
- Inter-leaf leakage
    - Tongue & groove (2-4%)
- Leaf-end leakage
    - Rounded leaf end (20%)
    - Flat leaf end (1-2%)



Intra-leaf leakage
0.8%

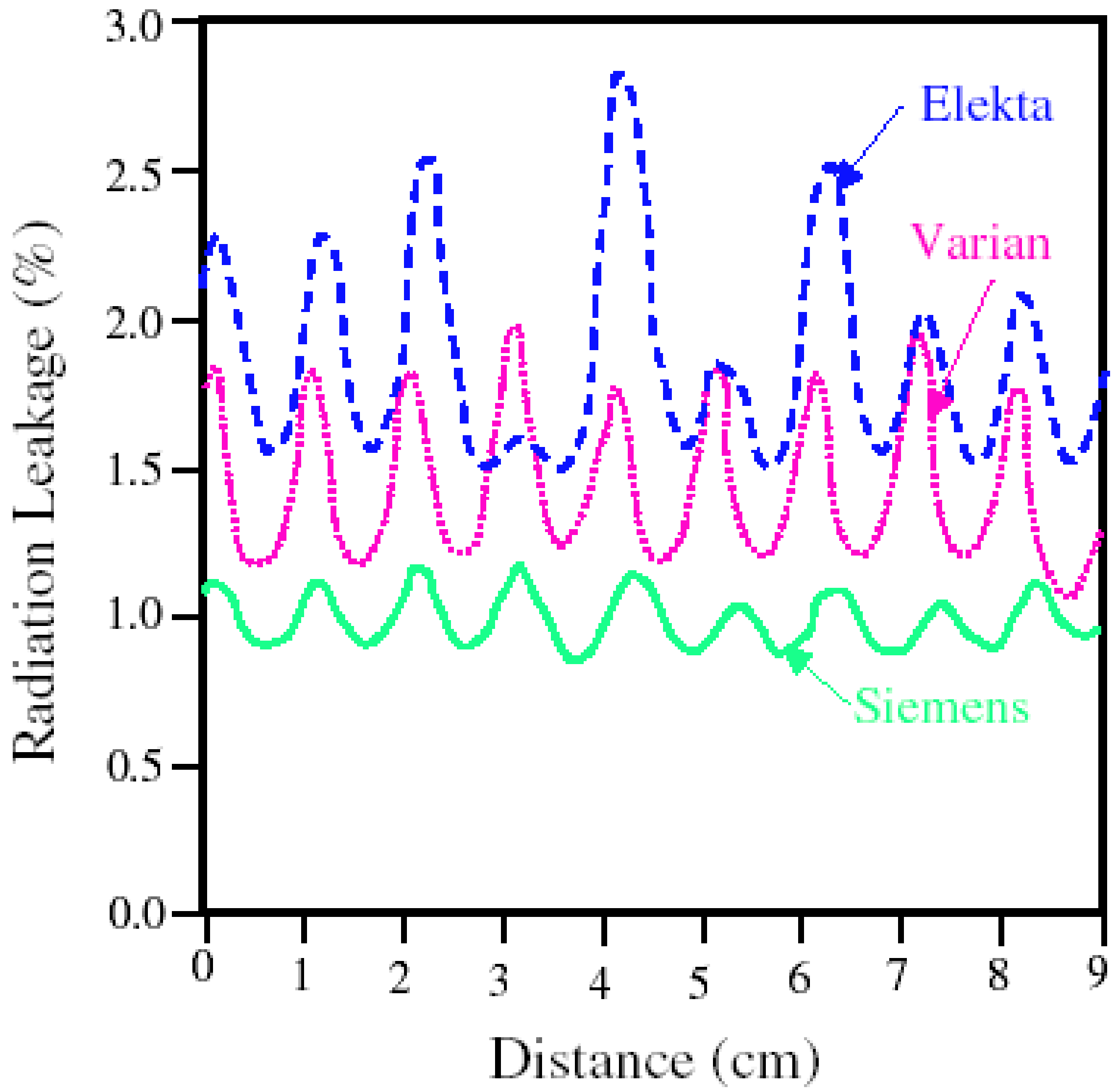
Inter-leaf leakage
(1.5%)

Leaf end leakage
(1.5%)

Siemens Primus
6MV

MLC Leakage and Backup Jaws

- MLC leakage can be minimized by letting backup jaws following each IMRT segment.
  - Varian: Backup jaws do not follow each MLC segment.
  - Siemens: Backup jaws follow each segment.
  - Elekta: Backup Jaws follow each segment.

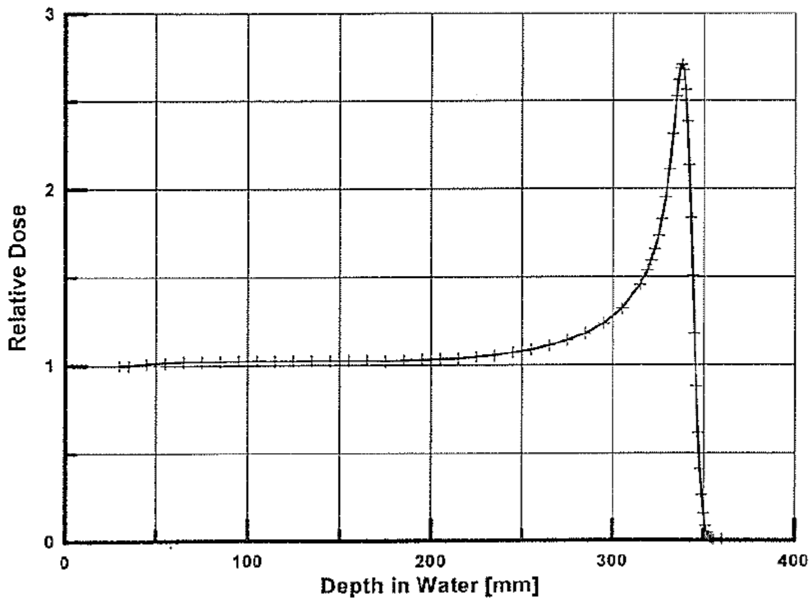


Huq, MS, et.al. *Phys Med Biol* 2002; 47: N159-70.

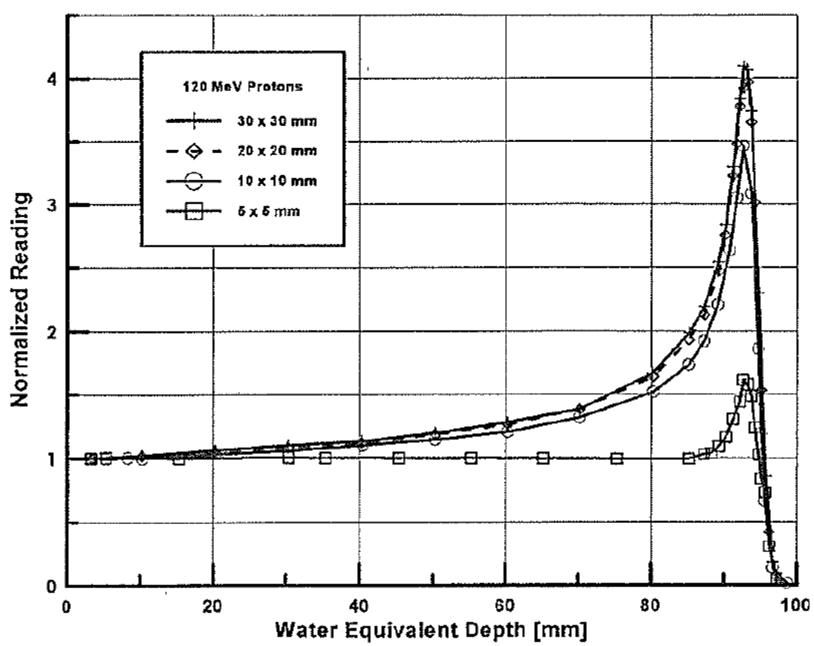
PROTON THERAPY

- Proton beams exhibit a Bragg peak effect, depositing a relatively large proportion of their initial energy at the end of their range.
- Bragg peak, in practice, is blurred by scattering foils, multiple coulombic scattering.
- Small fields exhibit a lower ratio of Bragg peak to entrance dose due to lateral side scatter.

- Proton beams have very sharp lateral penumbra for low energy protons and high energy protons (shallow depth).
- Allows for sharp separation between beam path and surrounding OARS - Big factor in deciding to treat patients with protons (aside from Bragg peak).



Relative Dose
Depth in Water [mm]
0
100
200
300
400
0
1
2
3



120 MeV Protons
30 x 30 mm
20 x 20 mm
10 x 10 mm
5 x 5 mm
Normalized Reading
Water Equivalent Depth [mm]
0
20
40
60
80
100
0
1
2
3
4

Requirements

- Energy of 200 – 250 MeV for penetration (e.g., prostate bilateral prostate treatment can be achieved with energies of 225 MeV).
- Supply about 5×10^{11} protons/minute for an average beam delivery time of less than 3 min per patient.

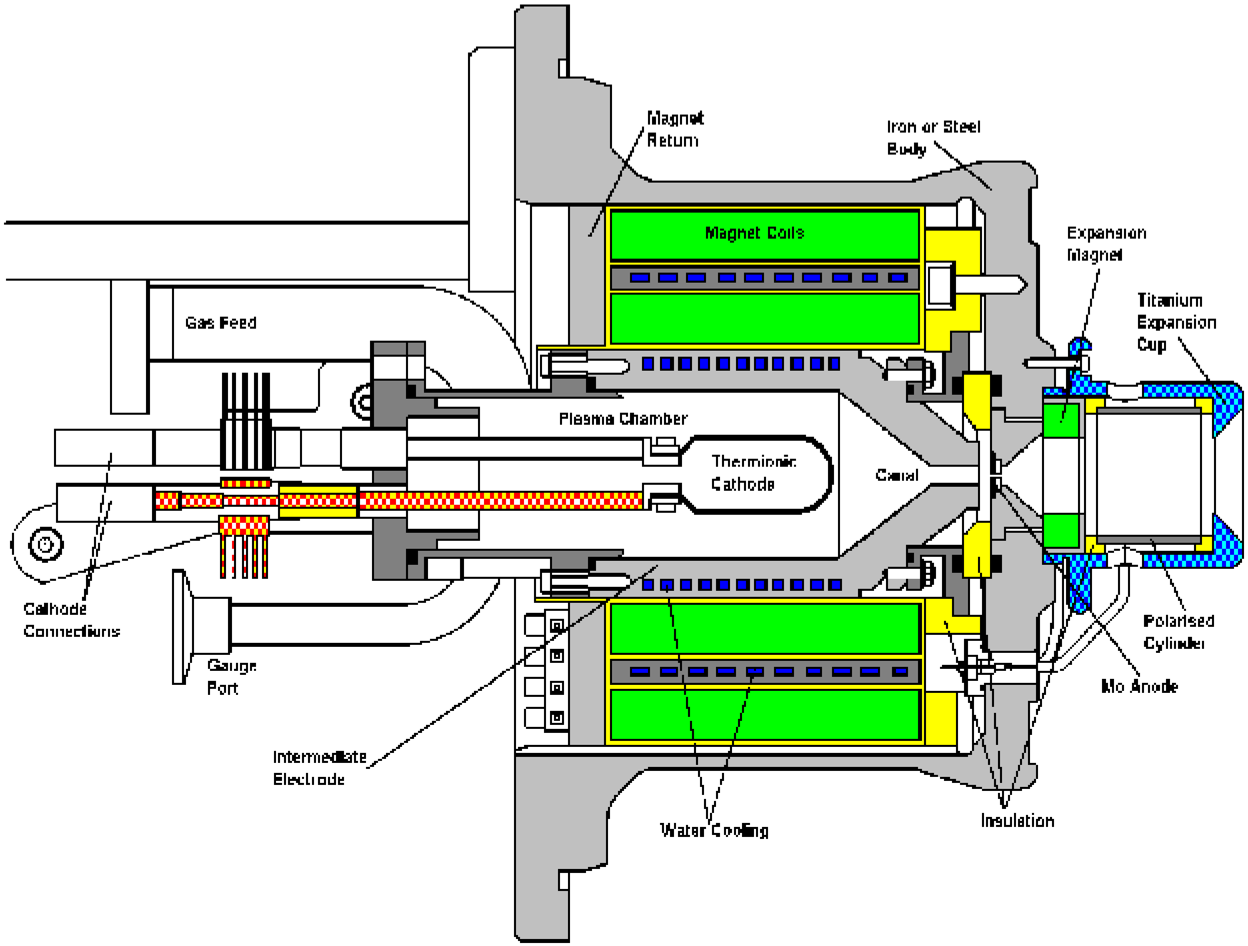
Equipment

- Duoplasmatron source
- Radio frequency quadrupole (RFQ) accelerator
- Synchrotron
- Beam line to treatment rooms

Duoplasmatron source

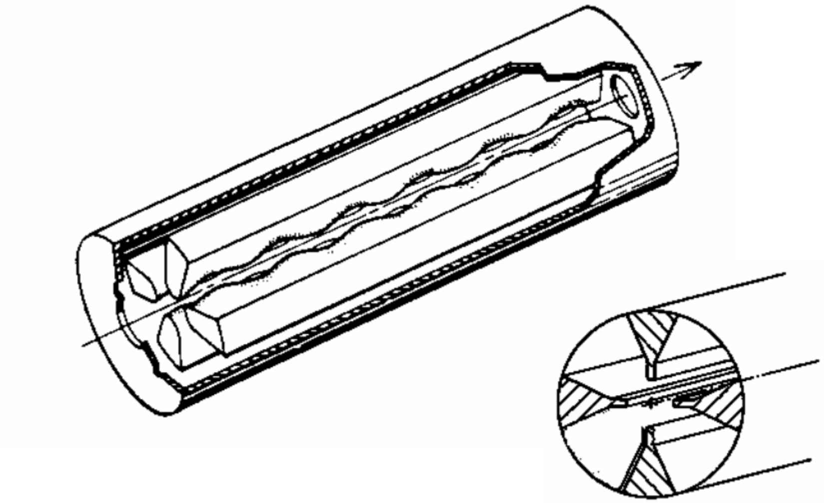
- Hydrogen gas is injected into high pressure chamber
- Filament creates electrons that mix with hydrogen to create a voltage arc that heats the hydrogen and turns it into a plasma.
- Solenoidal magnet is used to focus the electrons and protons created by plasma to pass through small opening into second chamber.
- Plasma cools in second chamber and electrons are attracted to chamber walls.
- Protons exit plasma surface and are accelerated by high voltage electrodes to RFQ accelerator.

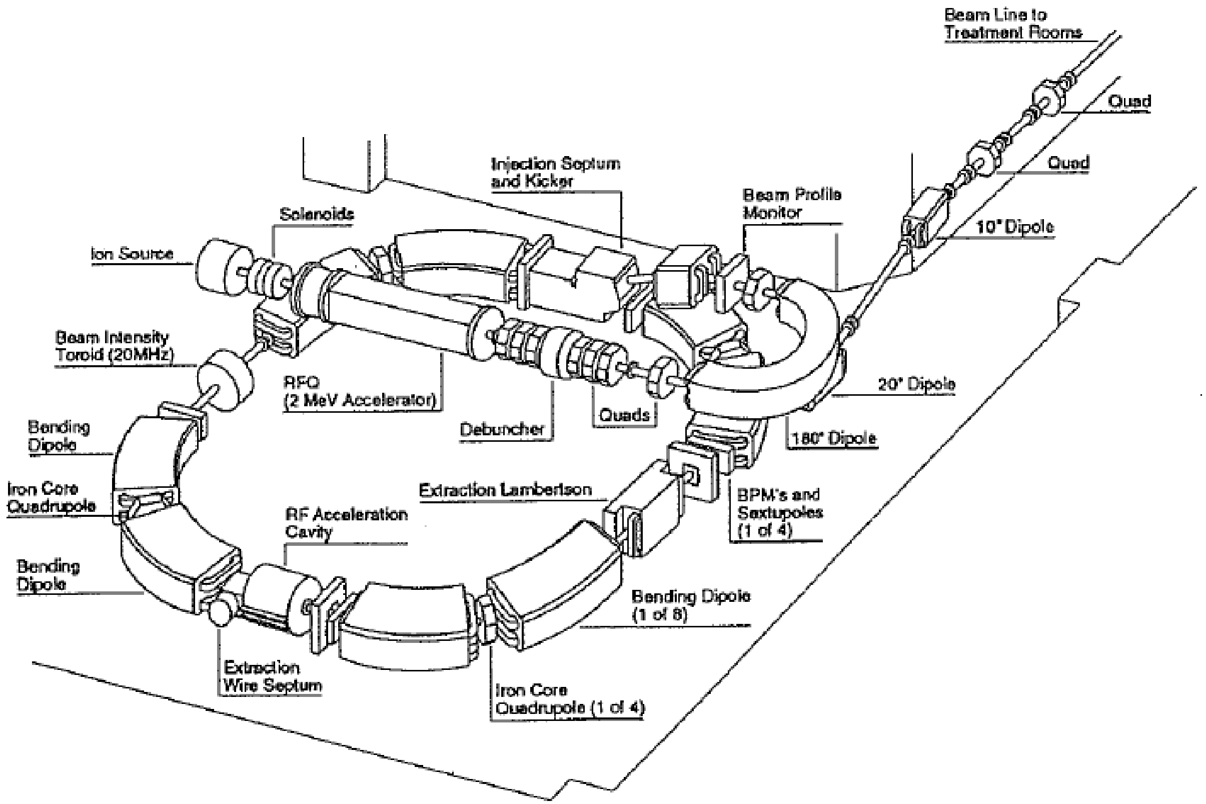
Duoplasmatron source



Radiofrequency quadrupole (RFQ) accelerator

- Enclosed box with 4 pole pieces having ridges down entire length.
- Radiofrequency power applied to poles produce axial electric field that accelerates protons and transverse magnetic field for focus.
- Proton energy at exit is about 2 MeV.





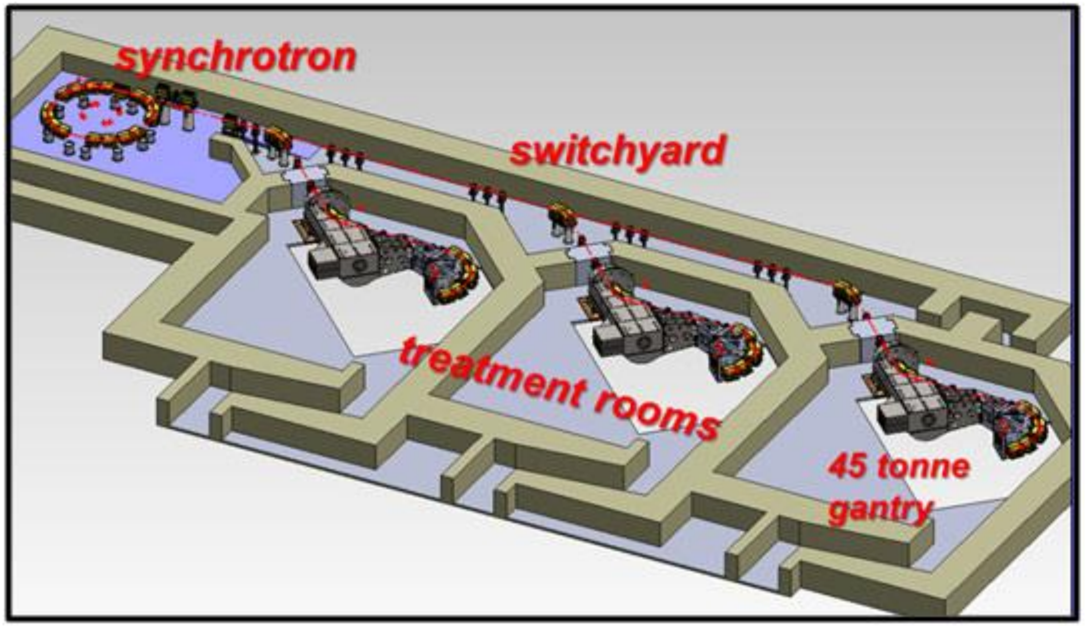
Protons exiting RFQ accelerator are turned 180° with bending magnet and injected into synchrotron.

Synchrotron

- Eight dipole magnets (2 at 4 corners) bend the protons around the synchroton.
- RF cavity accelerates the protons at each pass.
- Protons gain energy with each pass because of RF acceleration, so with each pass the dipole magnet strength must increase and RF frequency must increase.
- To reach energy of 250 MeV requires about 2.8 million passes.
- Once desired energy is reached, dipole magnetic strength and RF frequency are held constant to maintain energy.
- Beam is extracted to switchyard and then to treatment rooms.

Proton therapy switchyard

Treatment rooms could have rotating gantry or fixed gantry (fixed vertical, fixed horizontal).



Methods to produce laterally uniform fields

- Proton beam that comes out of synchrotron is a few mm wide.
- Need to be widened and made uniform across field for clinical use.

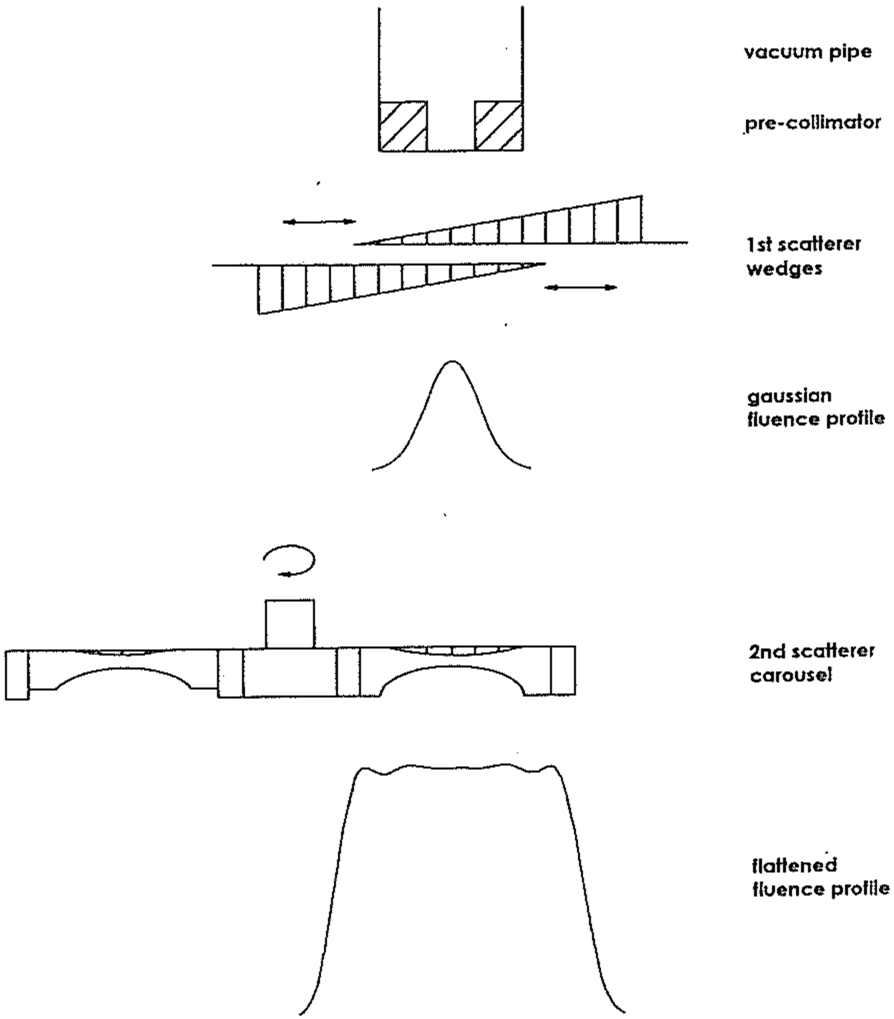
Techniques

- Scattering foils
- Raster scanning

Methods to produce laterally uniform fields

Scattering foils:

- Lead scatterer can be used to widen beam, but results in a gaussian (not flat) profile.
- A second scatterer that is approximately gaussian in shape is used to flatten beam.

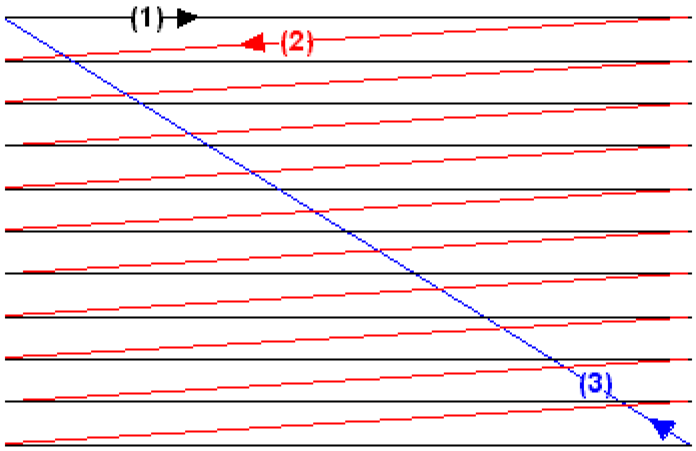


vacuum pipe
pre-collimator
1st scatterer wedges
gaussian fluence profile
2nd scatterer carousel
flattened fluence profile

Methods to produce laterally uniform fields

Raster scanning:

Narrow beam is steered across the field using magnets.



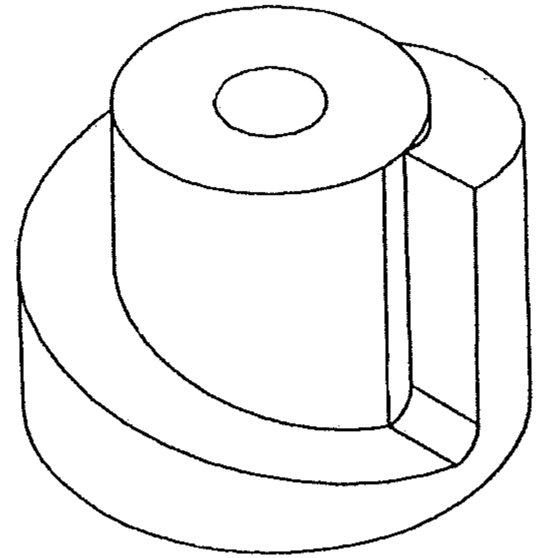
Modulating penetration of beam

- Tumors are at different depths in patients, so beam energy must be adjusted on a patient-specific basis.
- Within a specific patient, tumor maximum depth can vary across the field, so beam energy must be adjusted laterally.
- Within a specific patient, tumor minimum-to-maximum depth can vary across the field, so beam energy must be dynamically varied even at every point in the field.

Modulating penetration of beam

Tumors are at different depths in patients, so beam energy must be adjusted on a patient-specific basis.

- Range shifter spiral wedge can be used to tune the energy for a specific patient.
- Adds scatter and increases energy spread in the proton beam (creates undesirable energies).
- A bending magnet with collimator slits can be used to remove the undesirable energies.



Modulating penetration of beam

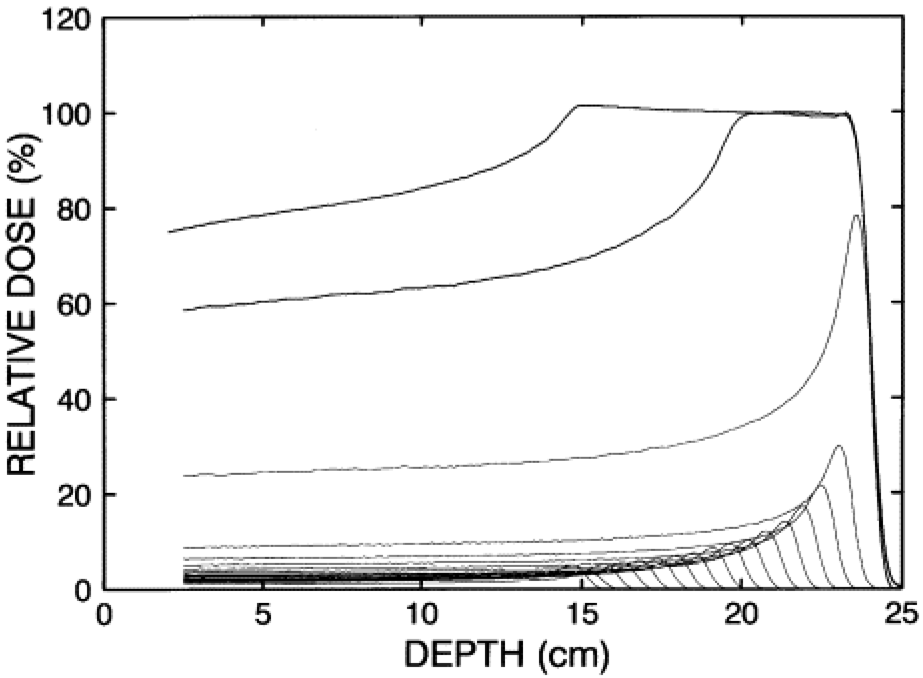
Within a specific patient, tumor maximum depth can vary across the field, so beam energy must be adjusted laterally.

- A plastic bolus with varying depths across the field using a computer-controlled milling machine that is linked to the treatment planning system.

Modulating penetration of beam

Within a specific patient, tumor minimum-to-maximum depth can vary across the field, so beam energy must be dynamically varied even at every point in the field.

- Spinning “propeller” inserts different thicknesses in front of beam, smearing the energy.

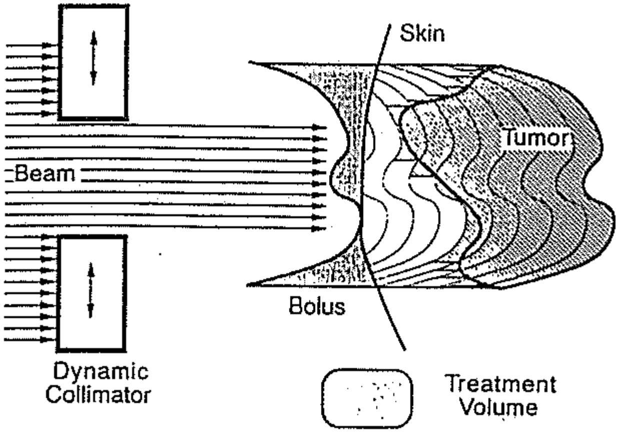


Final collimation at patient

- Similar to electrons – collimation needs to be done as close to patient as possible because of multiple coulombic scattering in bolus and air.
- Multiple cones are available – custom apertures are placed in cone to define field shape.
  - Cast from Lipowitz metal poured in a hotwire cut styrofoam mold.
  - For high precision, milled precisely from soft metal such as brass.

Intensity Modulated Proton Therapy

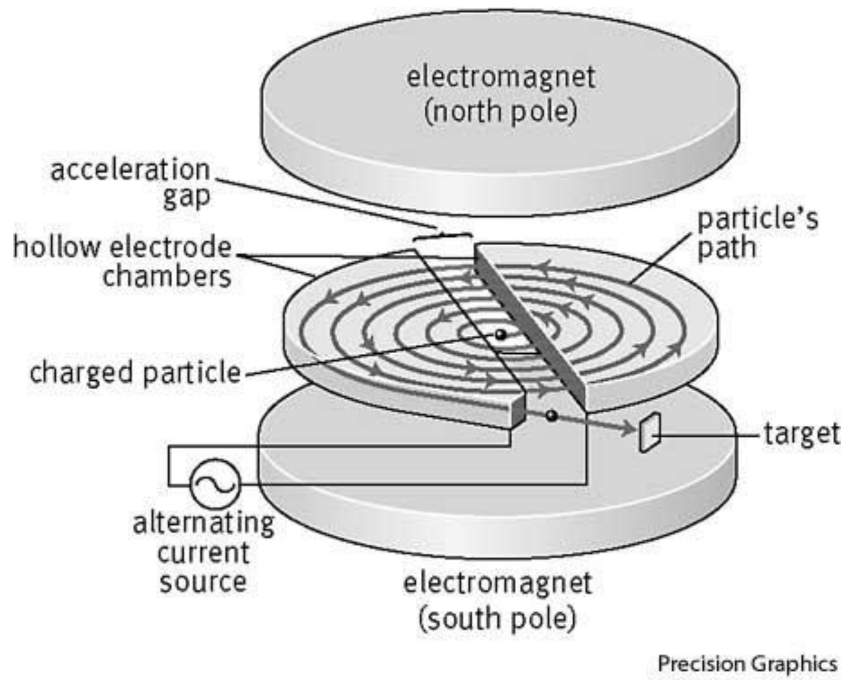
- Can be achieved using a range shifter, bolus (not necessarily needed), propeller and some method to control the beam fluence across the field.
- Beam fluence control.
  - ➢ Using an MLC.
  - ➢ Magnetic scanning of the beam in a controlled fashion to vary the fluence across field.



Other accelerators

Cyclotrons

- Acceleration of ions (protons, deuterons, heavier ions)
- Two evacuated Dees.
- Uniform magnetic field.
- Alternating electric field between electrodes that accelerate particles every time they cross electrodes.
- Magnetic field causes them to bend around.
- As particle energy increases, radius of bending increases, causing a spiral pattern to be traced.
- Can accelerate protons to about 10 MeV and deuterons to about 20 MeV.



Other Accelerators: Cyclotrons

Cyclotrons are used for: isotope production, particle therapy, neutron therapy (by hitting protons or deuterons on a beryllium target)