Chapter

3

Production of X-Rays

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Ui-Jung Hwang, PhD, KBMP, DABR
Chungnam National University Hospital

X-ray tube

Basic x-ray circuit

Voltage rectification

Physics of x-ray production

X-ray energy spectra

Operating characteristics

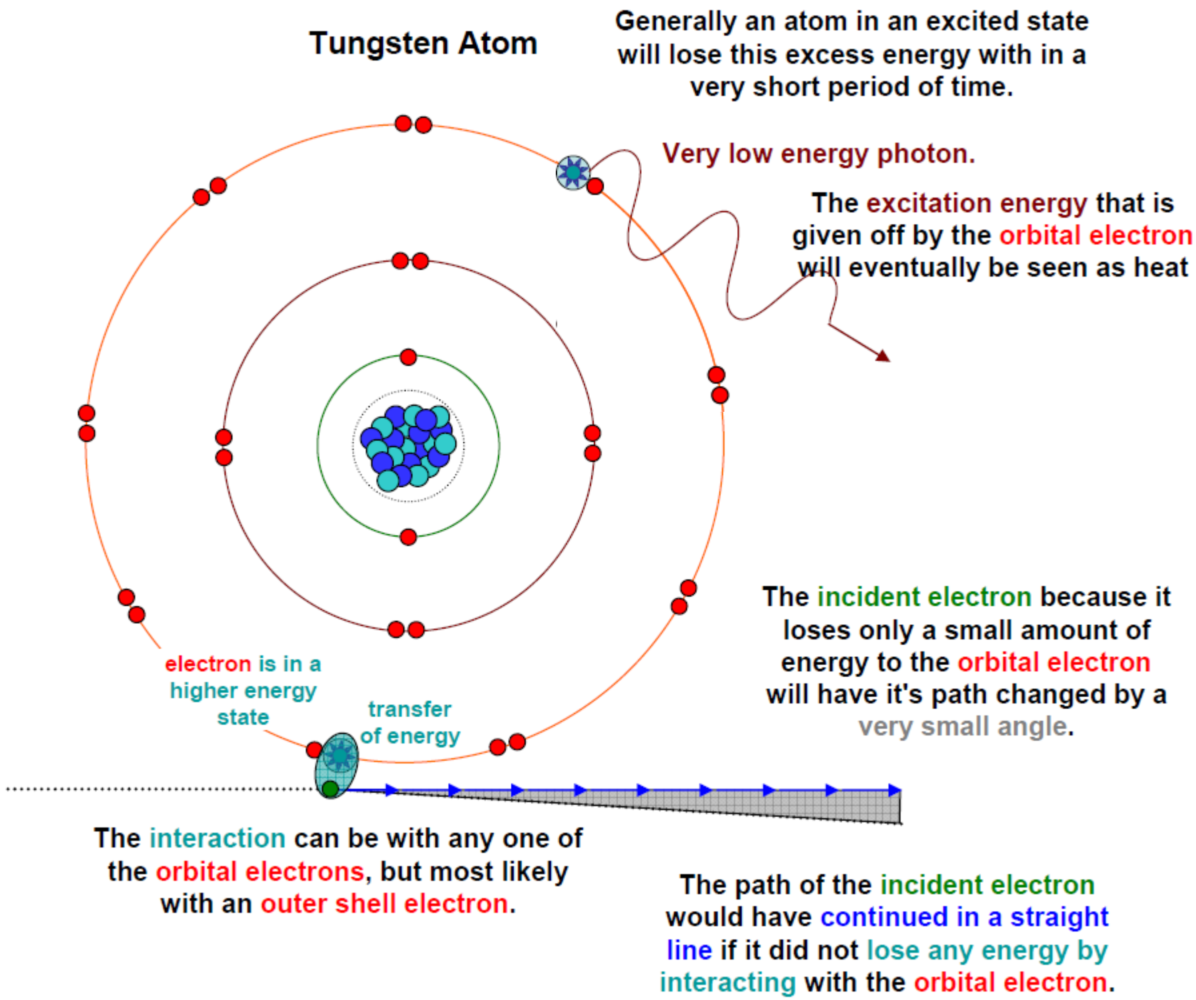
Dates

X-rays	1895 Roentgen
Radioactivity	1896 Becquerel & Curie
Cobalt-60	1950 Johns
Linear Accelerator	1960 Varian
Computerized Radiotherapy	1960 Cunningham
X-ray CT Scans	1972 Cormack & Hounsfield
Magnetic Resonance Imaging	1973 Lauterbur

X-ray Production

1. Excitation
2. Ionization
3. Bremsstrahlung

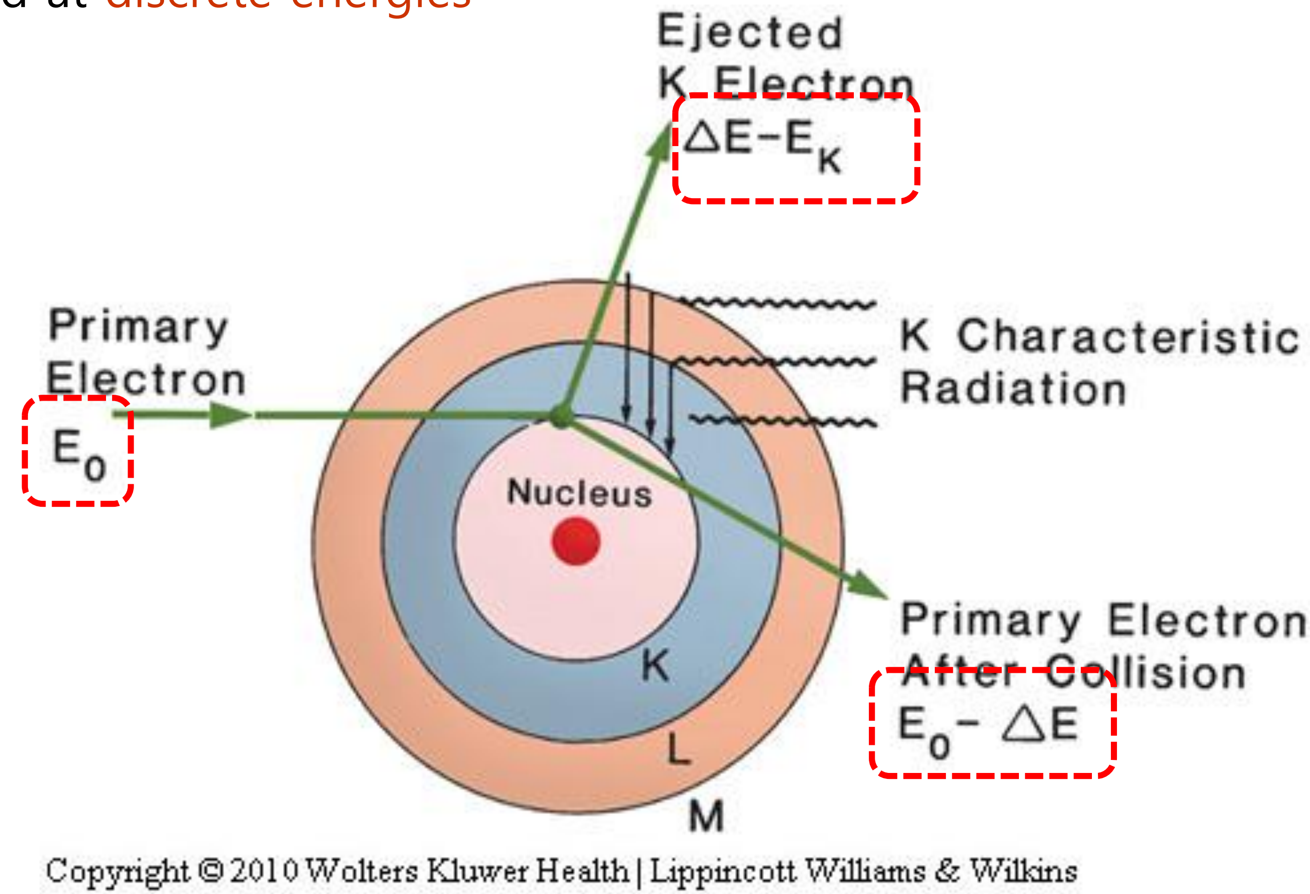
1.Excitation



2. Ionization (Characteristic X-ray)

❖ interact with atoms of the target by ejecting an orbital electron, leaving the atom ionized

❖ emitted at discrete energies



2. Ionization (Characteristic X-ray)

TABLE 3.1 Principal Characteristic X-ray Energies for Tungsten

Series	*Lines*	*Transition*	*Energy (keV)*
K Series	$K\beta_2$	$N_{III} - K$	69.09
	$K\beta_1$	$M_{III} - K$	67.23
	$K\alpha_1$	$L_{III} - K$	59.31
	$K\alpha_2$	$L_{II} - K$	57.97
L Series	$L\gamma_1$	$N_{IV} - L_{II}$	11.28
	$L\beta_2$	$N_V - L_{III}$	9.96
	$L\beta_1$	$M_{IV} - L_{II}$	9.67
	$L\alpha_I$	$M_V - L_{III}$	8.40
	$L\alpha_2$	$M_{IV} - L_{III}$	8.33

Data from U.S. Department of Health, Education, and Welfare. *Radiological Health Handbook*. Rev. ed. Washington, DC: U.S. Government Printing Office; 1970.

❖ Critical absorption energy

- threshold energy that an incident electron must possess in order to first strip an electron from the atom

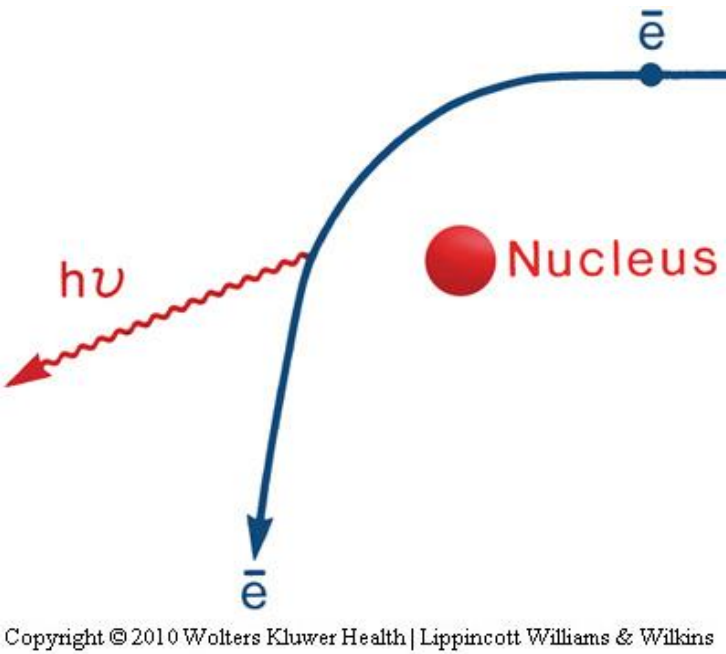
TABLE 3.2 Critical Absorption Energies (keV)

	Element											
Level	*H*	*C*	*O*	*Al*	*Ca*	*Cu*	*Sn*	*I*	*Ba*	*W*	*Pb*	*U*
Z	1	6	8	13	20	29	50	53	56	74	82	92
K	0.0136	0.283	0.531	1.559	4.038	8.980	29.190	33.164	37.41	69.508	88.001	115.59
L				0.087	0.399	1.100	4.464	5.190	5.995	12.090	15.870	21.753

Data from U.S. Department of Health, Education, and Welfare. *Radiological health handbook*. Rev. ed. Washington, DC: U.S. Government Printing Office, 1970.

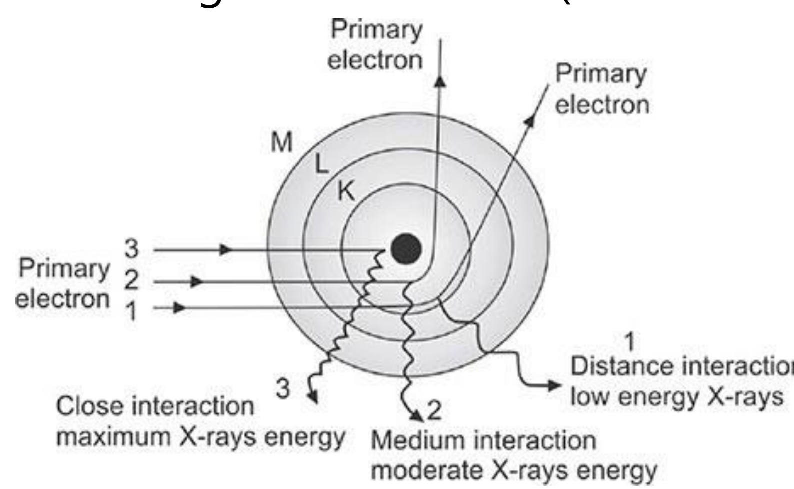
3. Bremsstrahlung radiaiton

- result of radiative "collision"(interaction)
  between a high-speed electron and a nucleus



- High speed **e** + Nucleus: Coulomb Interaction
  - Reduced speed of **e**
  - Reduced kinetic energy of **e**

➔ electromagnetic radiation (continuous energy)



- Maximum bremsstrahlung energy is initial energy of electron

- ❖ the direction of emission of bremsstrahlung photons depends on the energy of the incident electrons
- ❖ Megavoltage x-ray tube: transmission type target
- ❖ Low-voltage x-ray tube: reflection type target

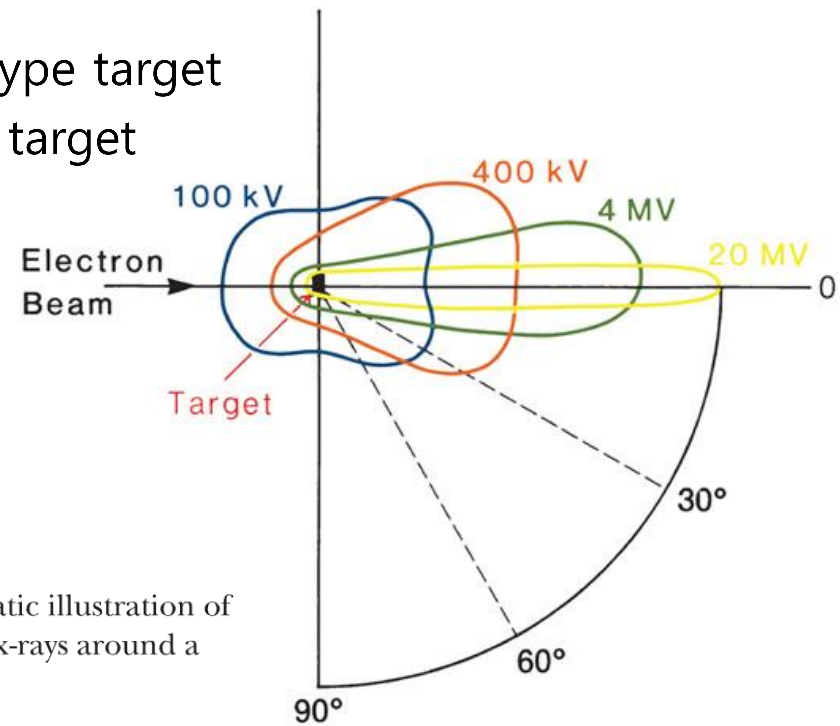
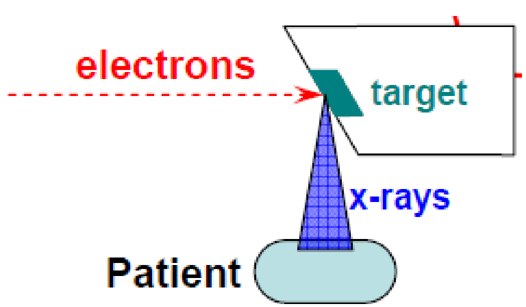
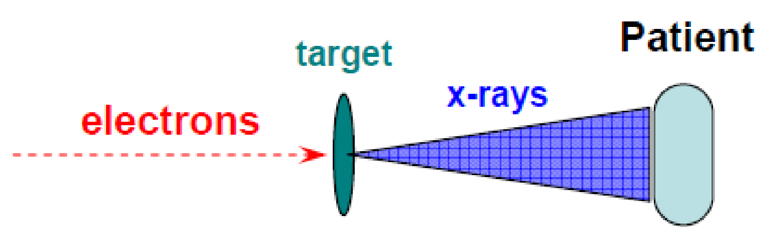


Figure 3.7. Schematic illustration of spatial distribution of x-rays around a thin target.

For low energy x-ray



For high energy x-ray



- the energy loss per atom by electrons depends on Z^2
  - probability of bremsstrahlung production ~ Z^2

- the efficiency of x-ray production: the ratio of output energy emitted as x-rays to the input energy deposited by electrons

  Efficiency=$9 \times 10^{-10} ZV$, if Z=74, V=100kV → Efficiency=1%,

  for high energy x-rays, it reaches 30~95% (6X→40%)

4. X-ray energy spectra

❖ heterogeneous in energy
 - continuous Bremsstrahlung + discrete characteristic

❖ If no filtration, neither inherent nor added,
Kramer's eqn, $I_E = KZ(E_m - E)$
max. photon energy E_m (in keV) = applied tube peak voltage (in kVp)

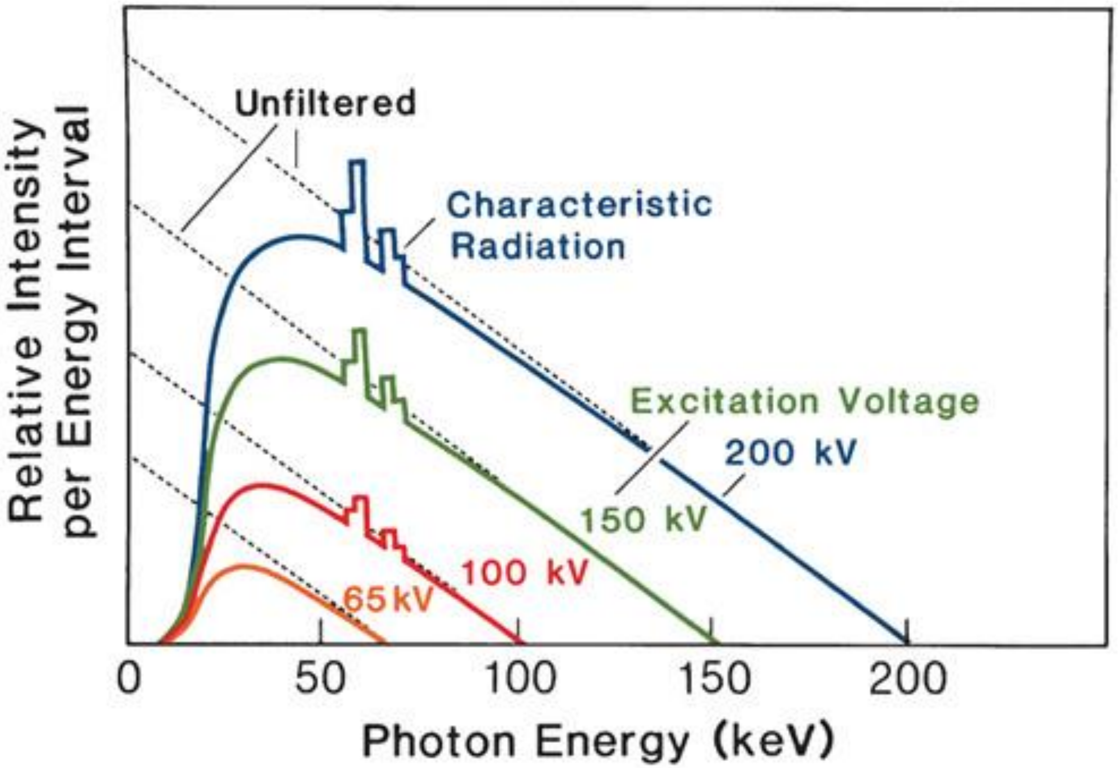


Figure 3.9. Spectral distribution of x-rays calculated for a thick tungsten target using Equation 3.1. *Dotted curves* are for no filtration and *solid curves* are for a filtration of 1-mm aluminum. (Redrawn from Johns HE, Cunningham JR. *The Physics of Radiology.* 3rd ed. Springfield, IL: Charles C Thomas; 1969, with permission.)

4. X-ray energy spectra

❖ Inherent filtration: target, glass walls of the tube, thin beryllium window
- equivalent to 0.5 ~ 1.0 mm aluminum

❖ Added filtration: Al or Cu, beam harden, improving the penetrating power

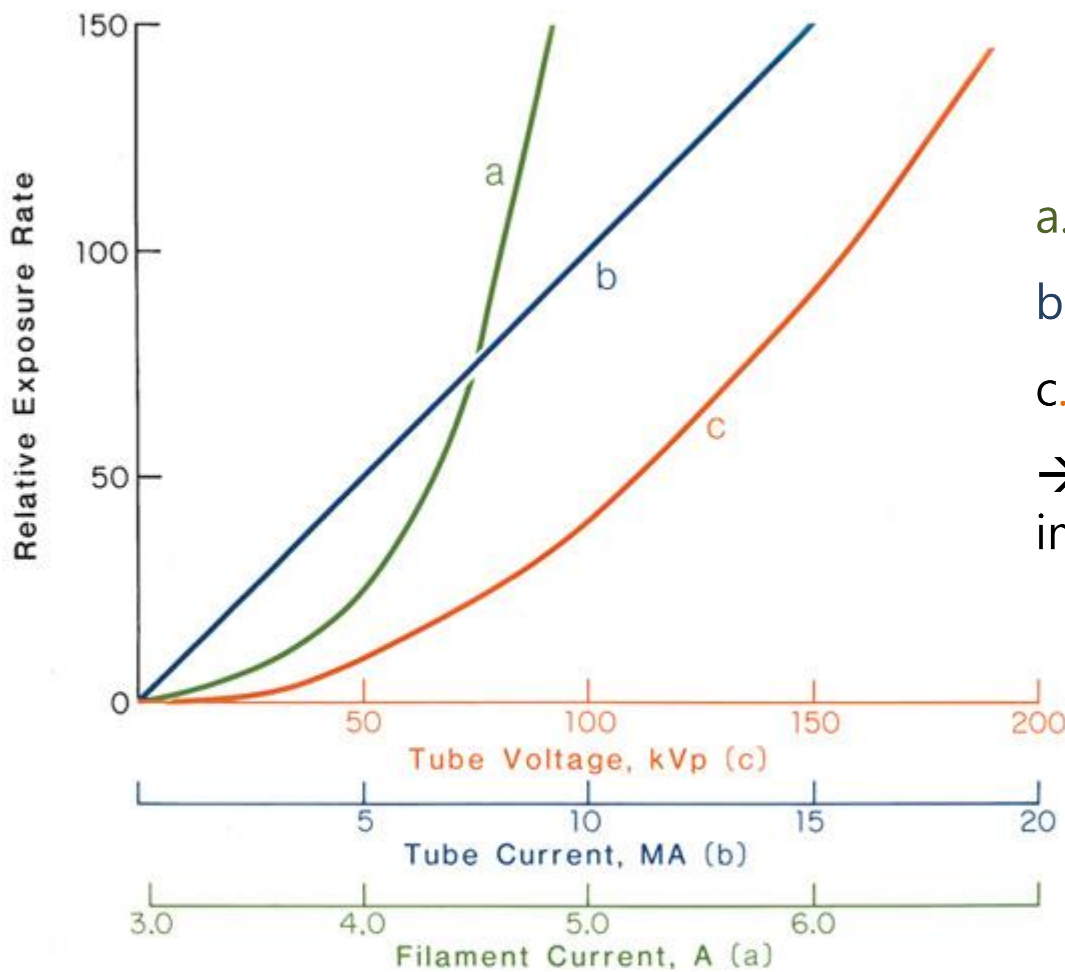
❖ Increasing the voltage: improving the penetrating power
- combination of voltage and filtration
  → achieve desired hardening and acceptable intensity

❖ The shape of the x-ray energy spectrum: the alternating voltage applied to the tube, multiple bremsstrahlung interactions within the target and filtration in the beam
- even if constant potential to tube, still be heterogeneous in energy because of the multiple bremsstrahlung

❖ Difficult to characterize the beam quality in terms of energy, penetrating power, or degree of beam hardening
→ beam quality: average energy and half-value layer
- The average x-ray energy: **1/3 of the maximum energy or kV_p**

5. Operating characteristics

❖ the relationships between x-ray output :
(a) filament current, (b) tube current, and (c) tube voltage



a. exponential increase.

b. Linear

c. square

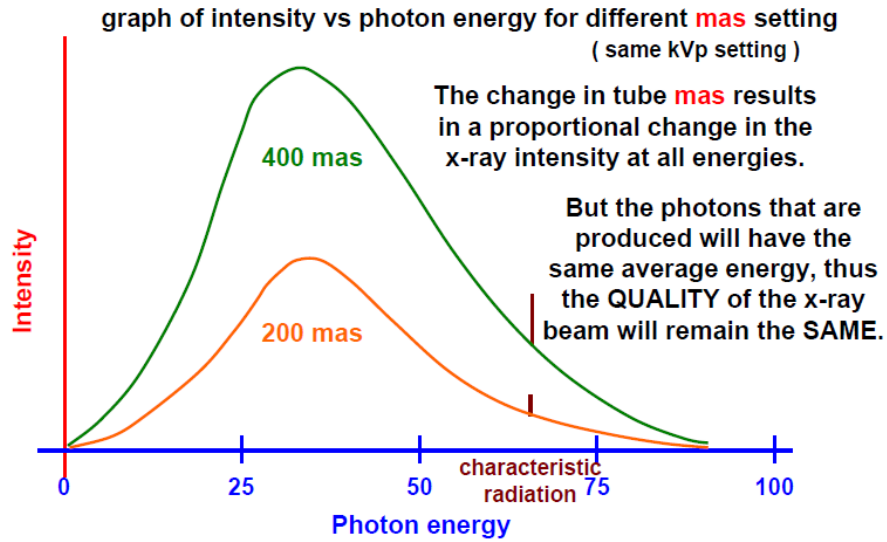
→ Stable filament current is important for stable output.

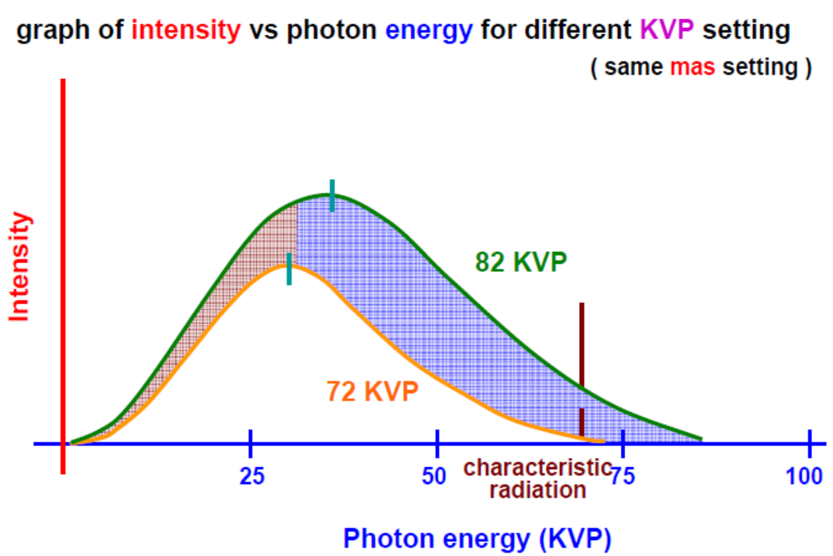
Intensity and energy spectrum

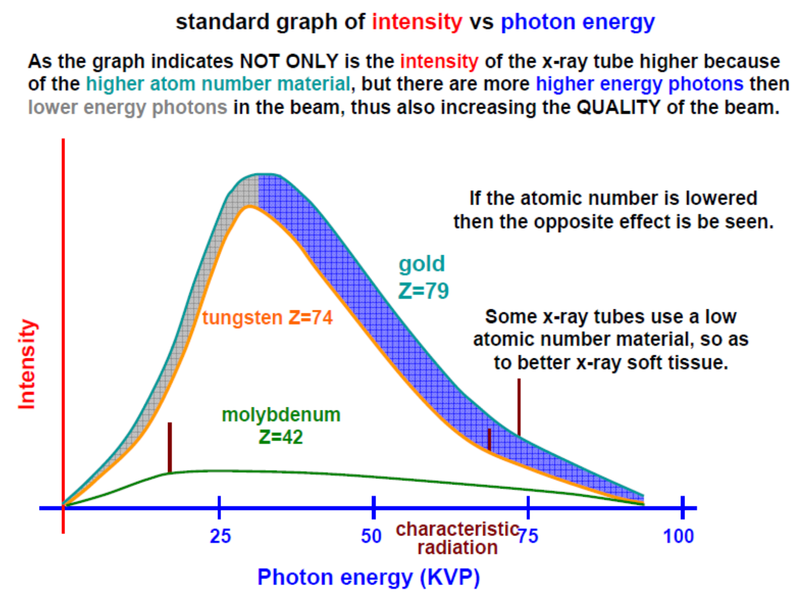
mAs: intensity of X-ray

kVp: intensity and energy spectrum

Target: depend on atomic number

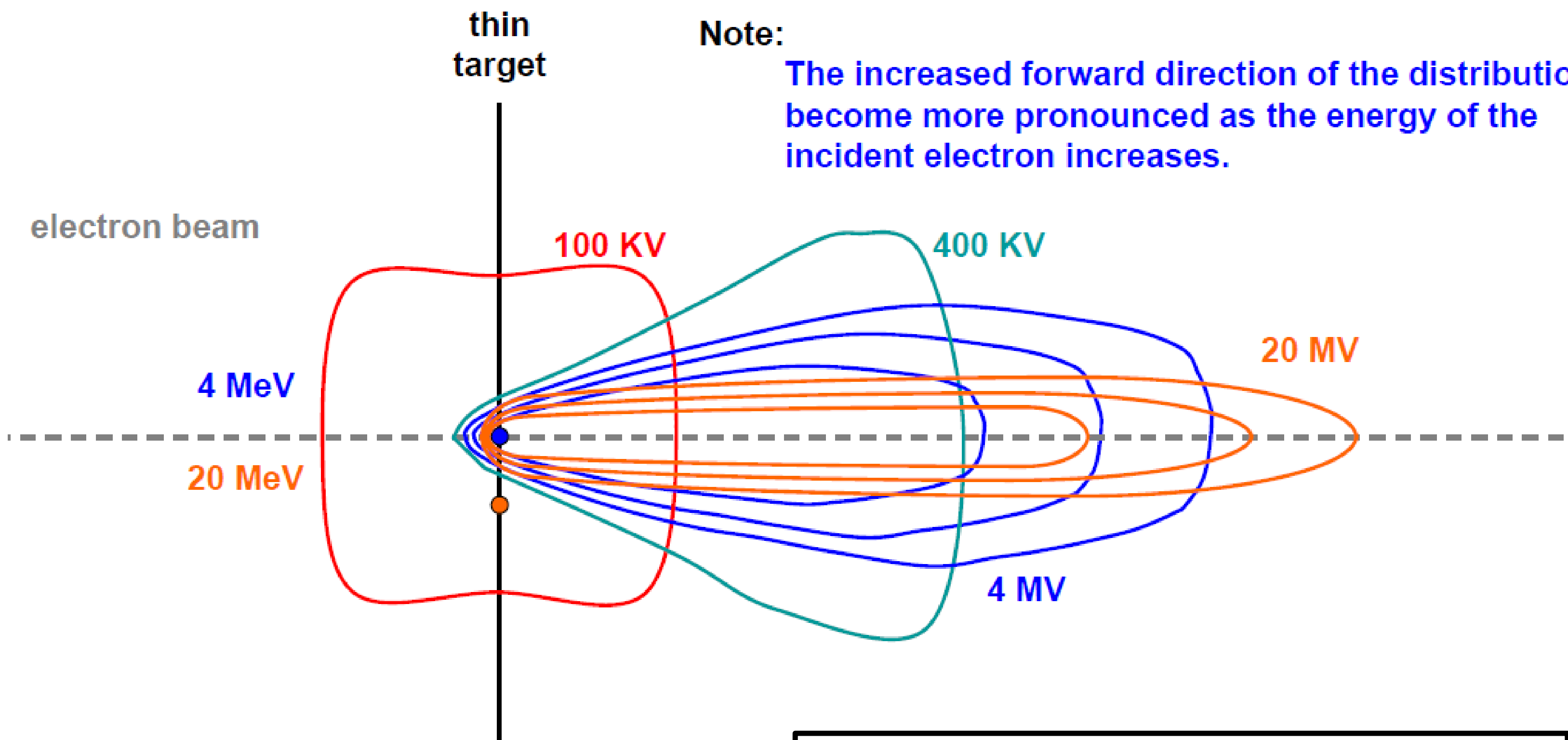


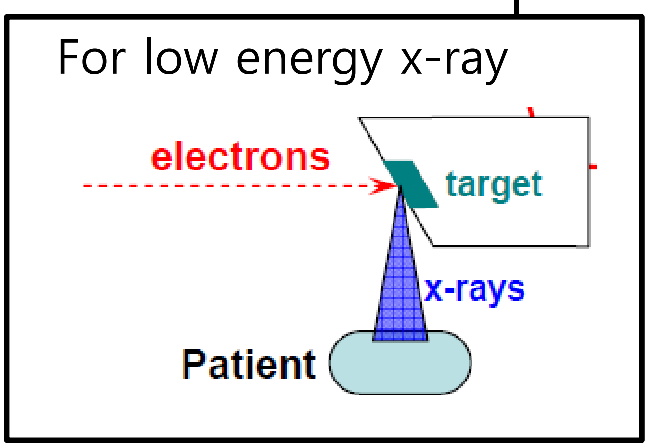


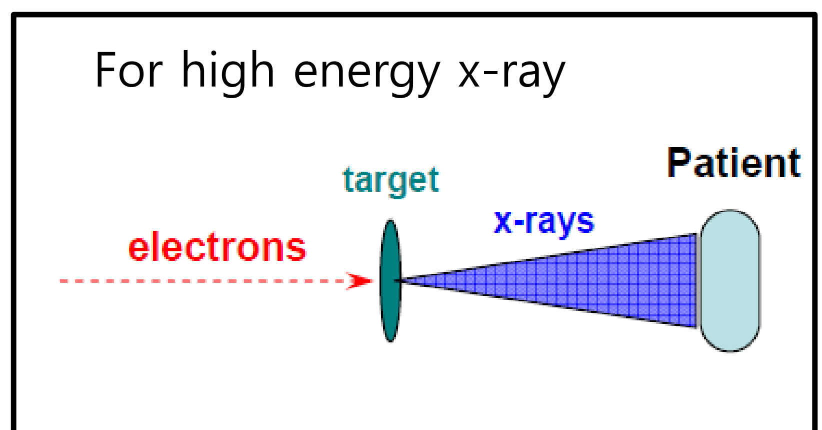


X-ray distribution around target

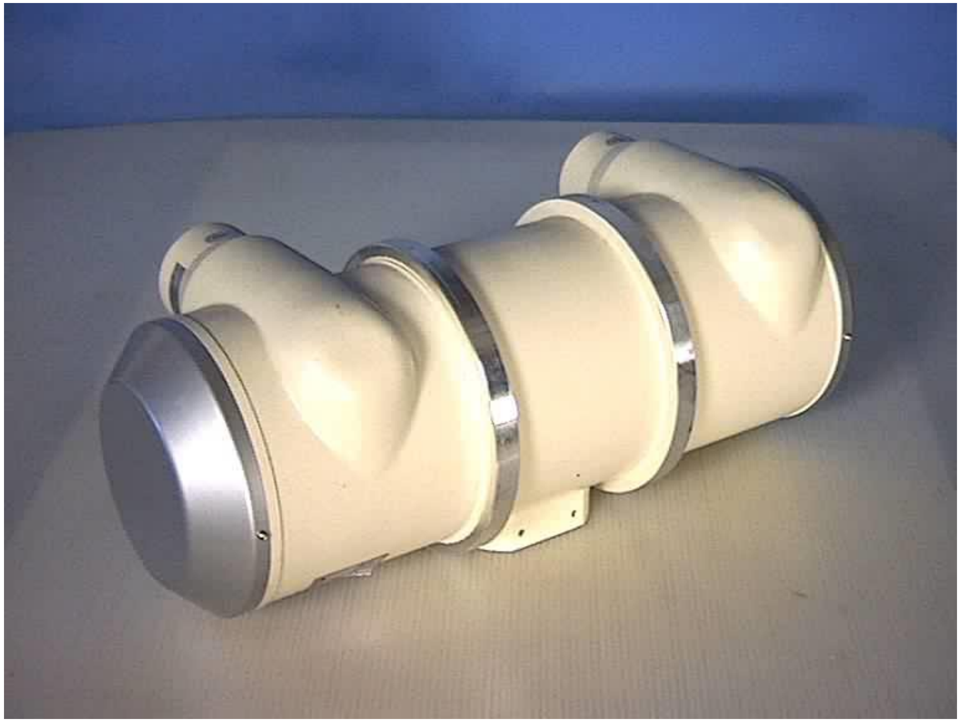
Note:
The increased forward direction of the distribution become more pronounced as the energy of the incident electron increases.



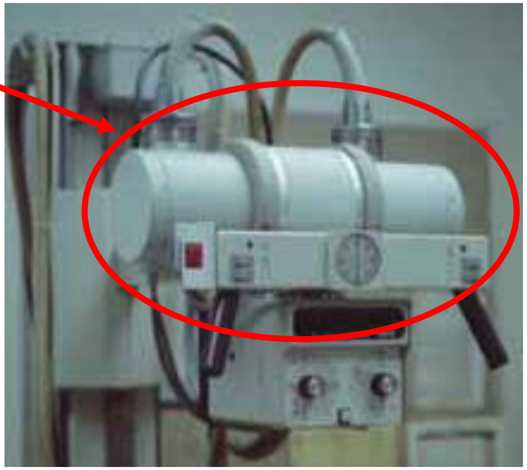


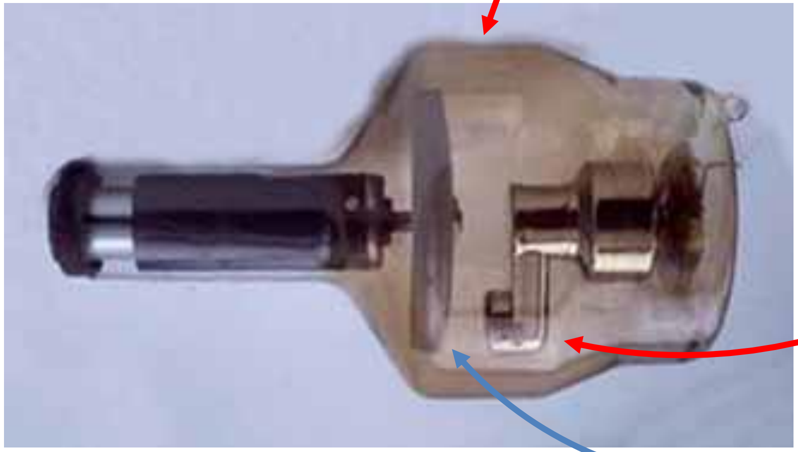


X-ray tube



- Housing
  - Visible part of tube
- Glass Enclosure (insert)
  - Vacuum
  - Electrodes
    - Cathode
      - Filament
    - Anode
      - Target





X-ray tube

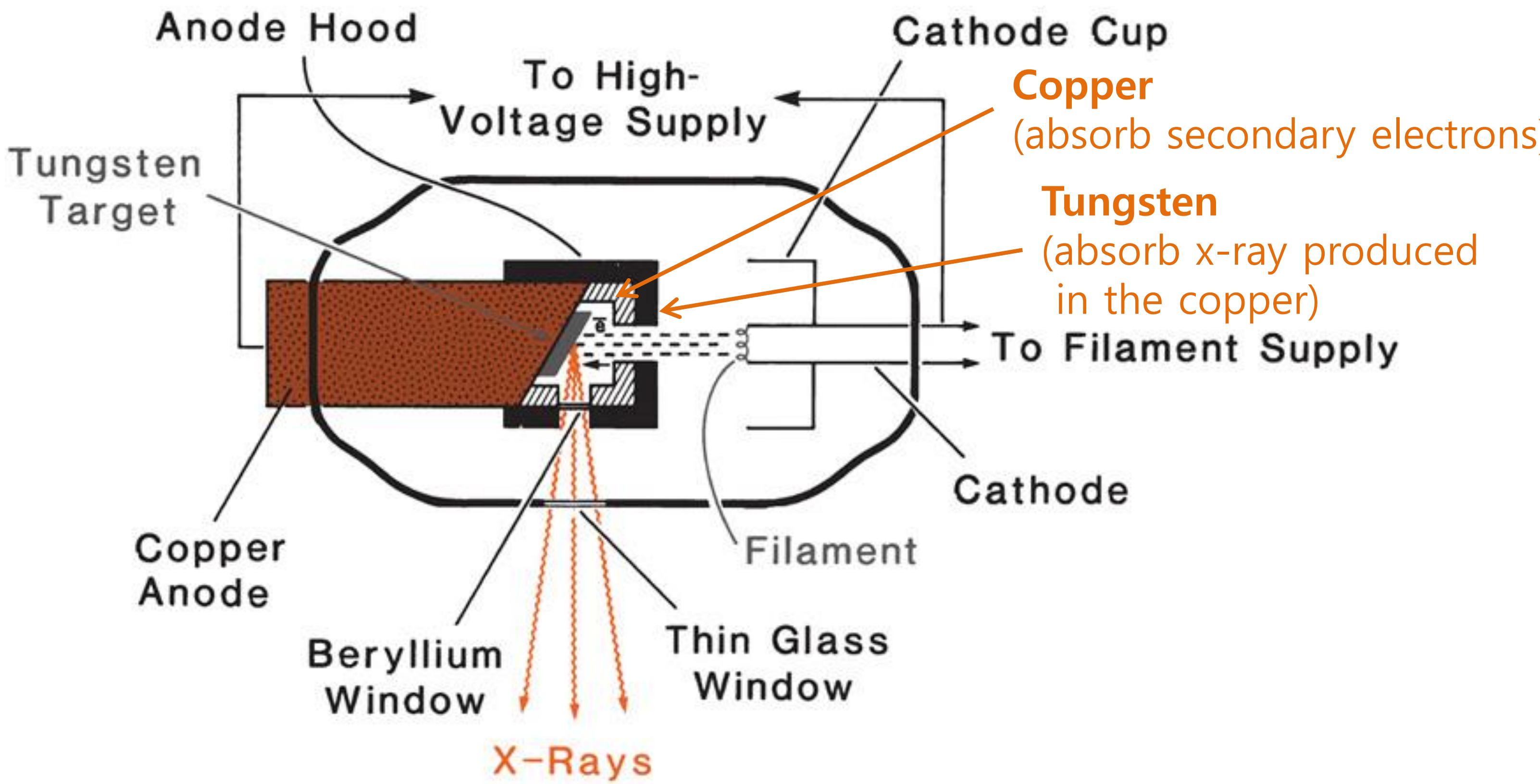


Figure 3.1. Schematic diagram of a therapy x-ray tube with hooded anode.

❖ Thin beryllium windows to reduce inherent filtrations of the x-ray beam

X-ray tube

A. The anode

- ❖ tungsten as the target material: high atomic number and high melting point

  The efficiency of x-ray production depends on the atomic number:
  Tungsten Z=74, a melting point of 3,370^{0}C

- ❖ efficient removal of heat from the target: a thick copper anode to the outside of the tube cooled by oil, water, or air, and rotating anodes

- ❖ Function of the oil bath: 1. insulate the tube housing from high voltage,
  2. absorb heat from the anode

X-ray tube

A. The anode

❖ Anode hood (copper inside and tungsten shield outside) to prevent stray electrons from striking the walls or other non-target components of the tube

- Cooper: absorb the secondary electrons produced from the target
- Tungsten: absorb the unwanted x-rays produced in the copper

❖ focal spot: as small as possible for producing sharp radiographic Images

❖ smaller focal spots generate more heat per unit area of target and, therefore, limit currents and exposure.

X-ray tube

❖ principle of line focus
  - apparent focal spot size can be reduced by the principle of line focus

A side of actual focal spot

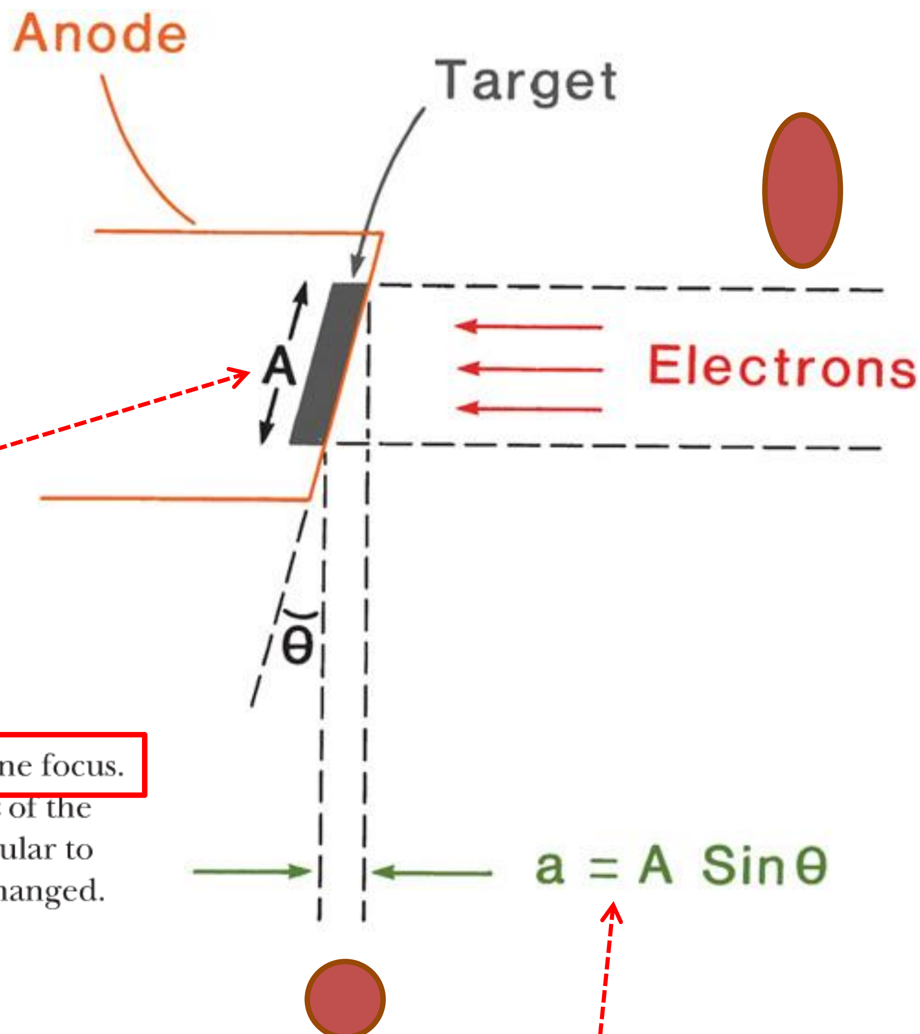
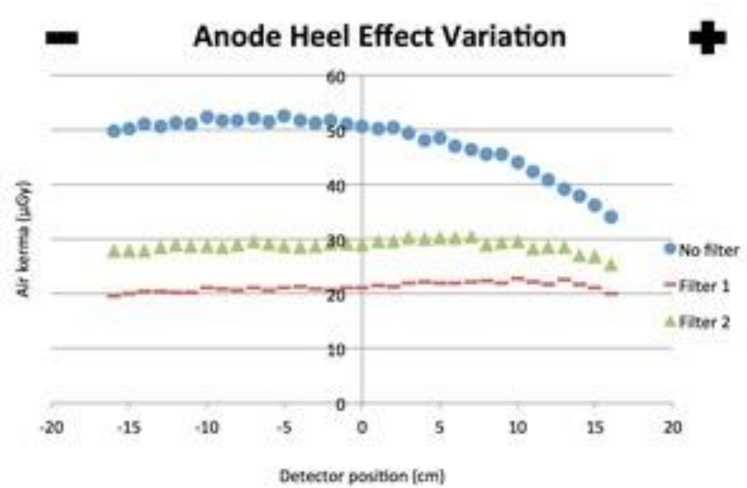


Figure 3.2. Diagram illustrating the principle of line focus. The side *A* of the actual focal spot is reduced to side *a* of the apparent focal spot. The other dimension (perpendicular to the plane of the paper) of the focal spot remains unchanged.

Apparent side

X-ray tube

- In diagnostic radiology, the target angles small (6-17 degrees) making focal spot sizes from 0.1x0.1 to 2x2 mm
- In therapy tubes, the target angle large (about 30 degree) making focal spot sizes from 5x5 to 7x7 mm
- greater attenuation for x-rays coming from greater depths than those from near the surface of the target : the heel effect → compensator used

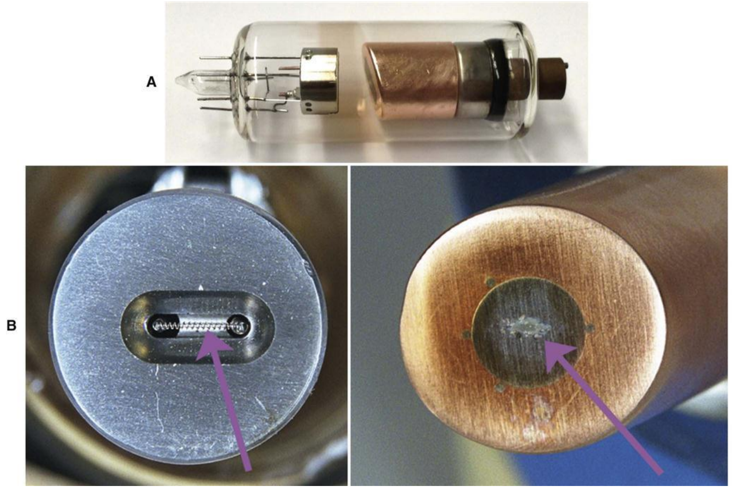


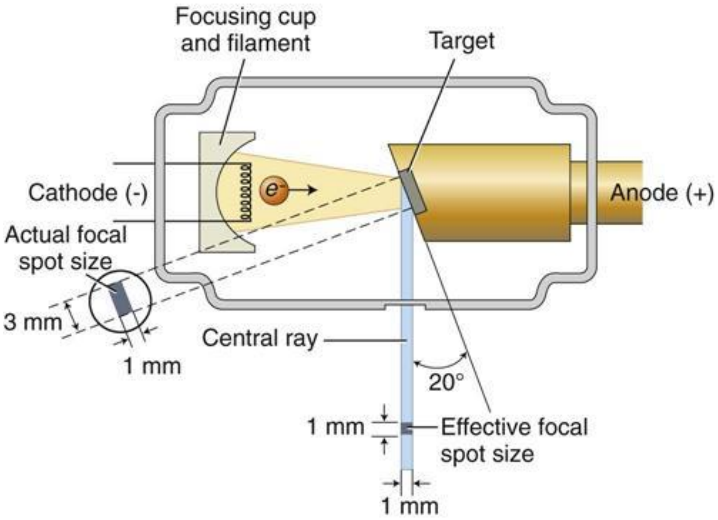
B. The cathode

❖ wire filament and a negatively charged focusing cup (cathode cup)
  - direct the electrons to strike the target in a well-defined area

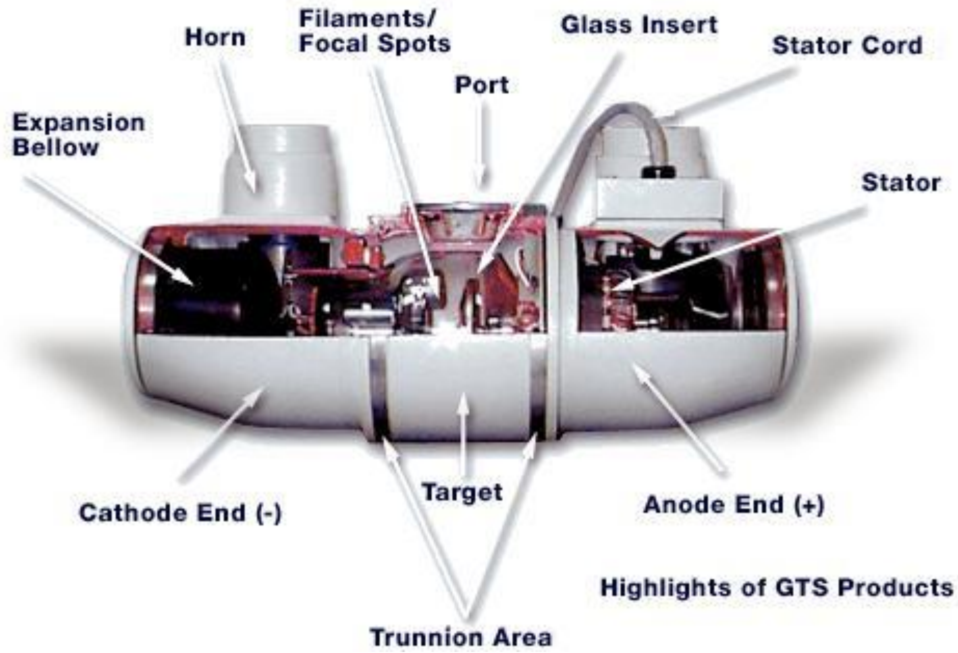
❖ the diagnostic tubes: two separate filaments to provide dual-focus
  - focal spot size depends on filament size
  - one provide small focal spot and the other large

❖ filament material
  - tungsten + 1~3% thorium (better emission of electrons)
  - less tendency to vaporize

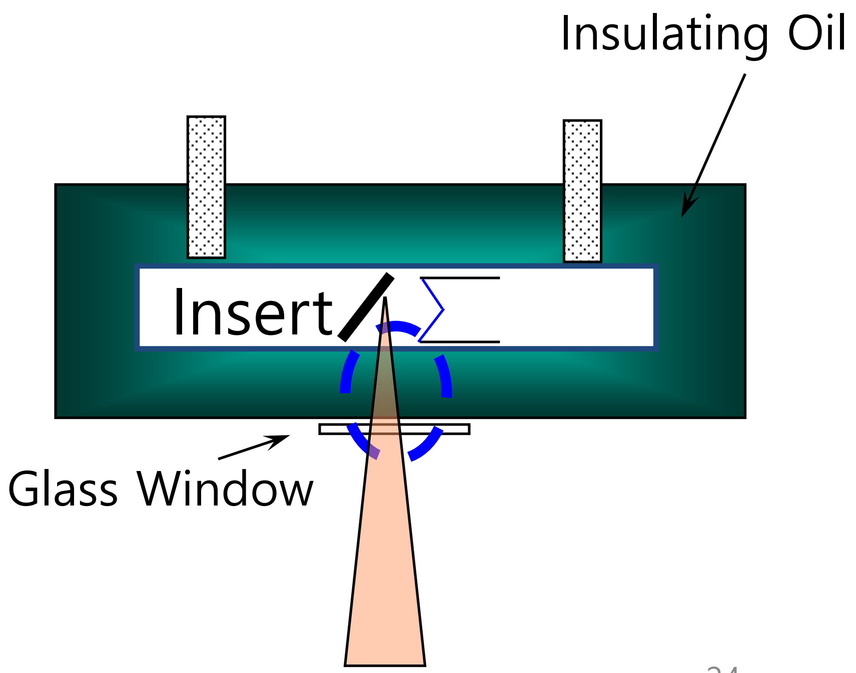




Inherent Filtration

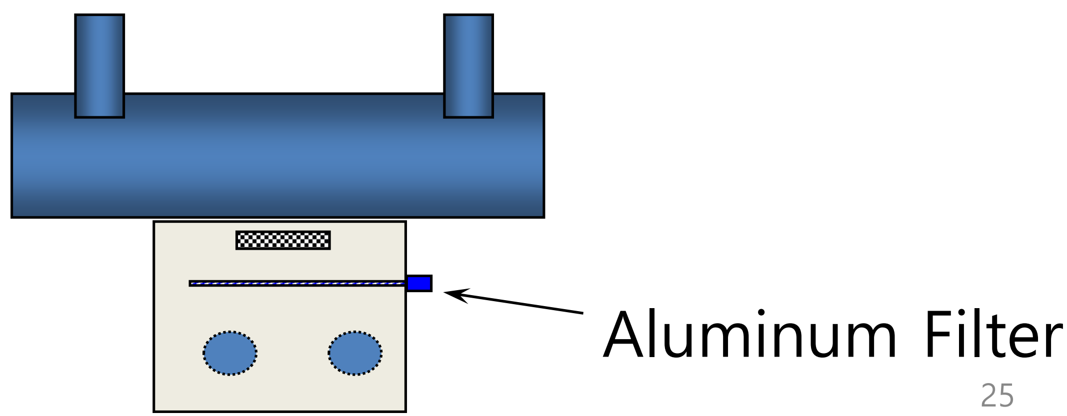


- Absorption of x-rays by tube
  - glass insert
  - insulating oil
  - housing window



Practical Filters

- Aluminum
  - Most common
  - atomic # 13
  - inexpensive
- copper
  - good for high kVp
  - sometimes used in combination with aluminum
    - aluminum absorbs copper's 8 keV characteristic radiation



3.2. Basic X-ray circuit

❖ high voltage circuit to provide the *accelerating potential for the electrons* and the low voltage circuit to supply *heating current to the filament*

❖ filament temperature or filament current controls the tube current and hence the x-ray intensity

❖ Low voltage circuit
  - Filament supply 10 V at about 6 A.
  - Step-down transformer

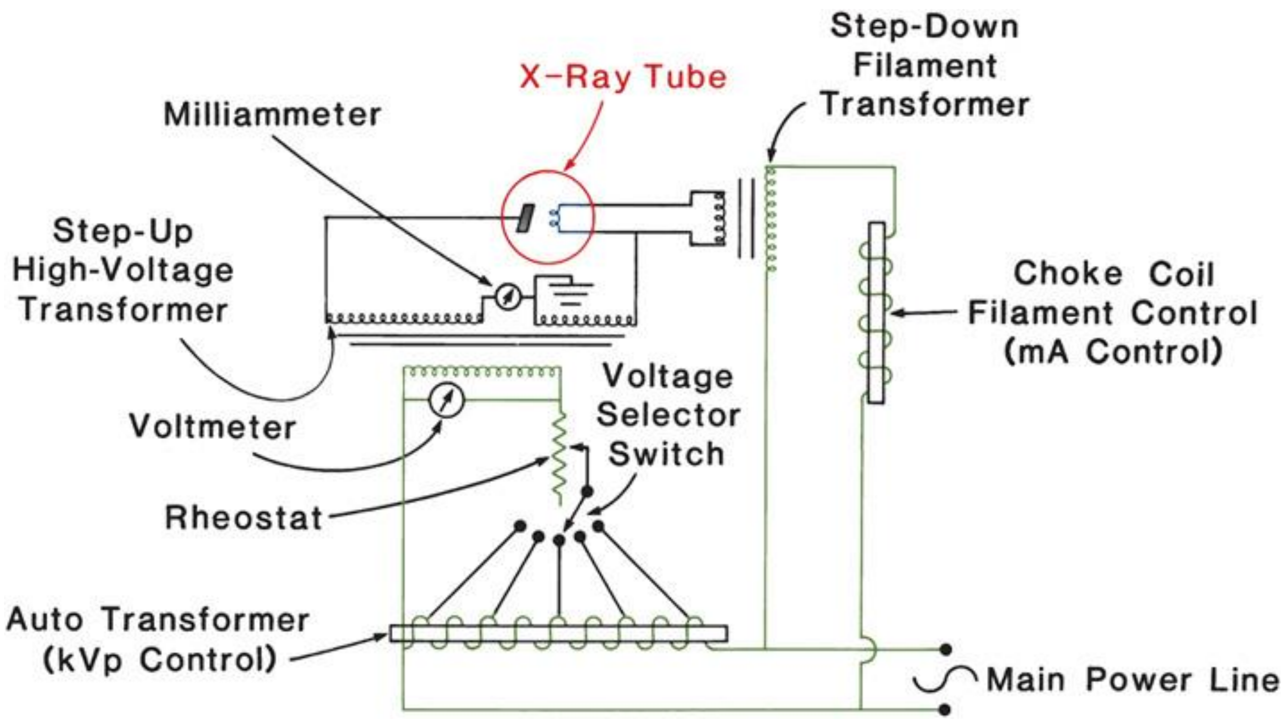
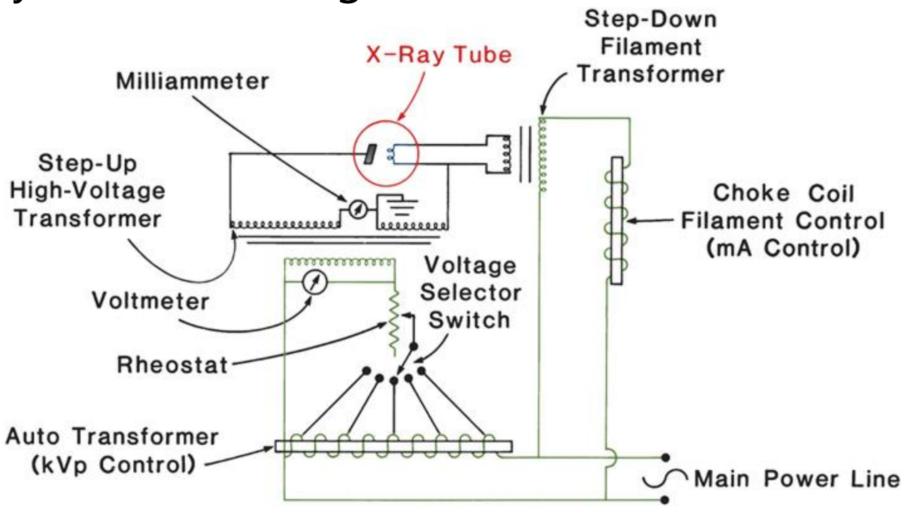


Figure 3.3. Simplified circuit diagram of a self-rectified x-ray unit.

❖ High voltage circuit
  - Step-up transformer
  - connected to autotransformer and rheostat
  - Autotransformer: provide a stepwise adjustment in voltage
  - Rheostat: variable resister
  - appreciable power loss in rheostat whereas low in an inductance coil

❖ Tube (peak) voltage measurement: sphere gap method
  - two metallic spheres separated by an air gap
  - relationship b.t. voltage, diameter of the spheres, distance at the instant that the spark first appears

❖ Tube current can be read on a milliammeter placed at the midpoint of the x-ray transformer secondary coil which is grounded



❖ Peak voltage and frequency

- if line voltage 220 V at 60 cycles / sec

  → peak voltage: $220\sqrt{2} = 311V$

- if transformer turn ratio, 500:1 → peak voltage: $220\sqrt{2} \times 500 = 155.6\,k\,V$

3.3. Voltage rectification

- no x-rays during the inverse voltage cycle for self-rectified circuit (an inverse electron current destroyed the filament)
- solved by using voltage rectifiers.
- Half-wave rectification

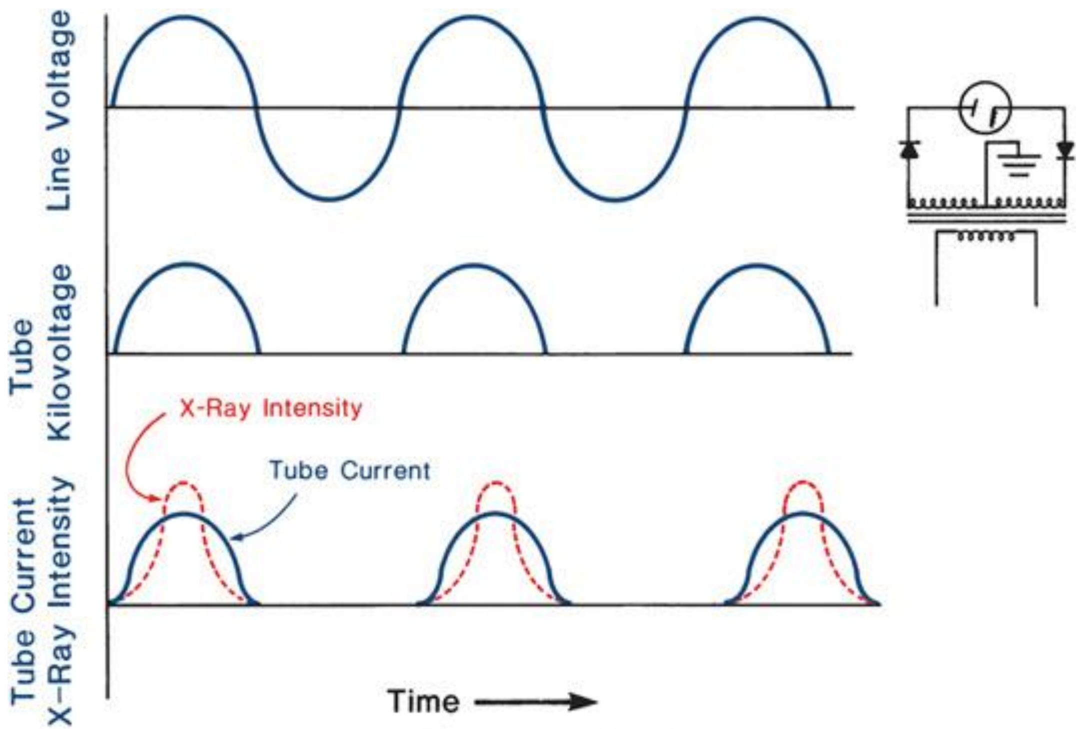


Figure 3.4. Graphs illustrating the variation with time of the line voltage, the tube kilovoltage, the tube current, and the x-ray intensity for self- or half-wave rectification. The half-wave rectifier circuit is shown on the right. Rectifier indicates the direction of conventional current (opposite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

❖ Full-wave rectification
  - electron for negative A: ABCDEFGH
  - electron for positive A: HGCDEFBA

❖ Smoothing condenser: keep nearly constant tube voltage

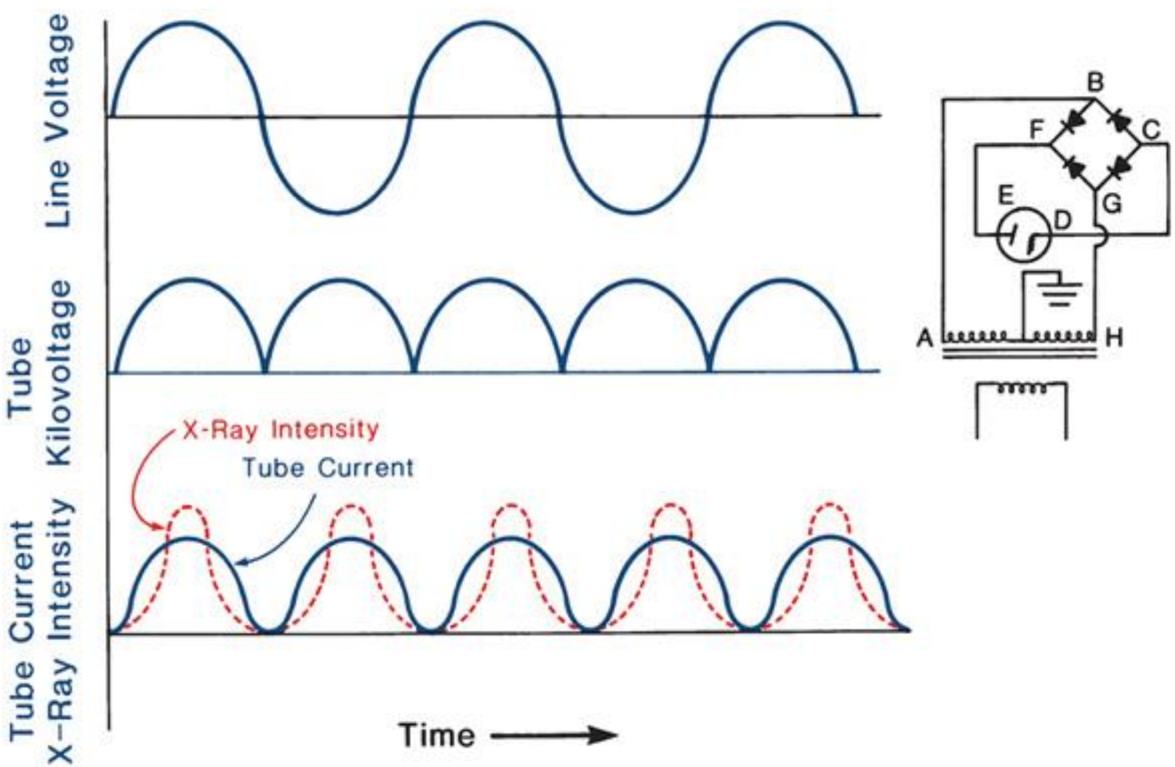


Figure 3.5. Graphs illustrating the variation with time of the line voltage, the tube kilovoltage, the tube current, and the x-ray intensity for full-wave rectification. The rectifier circuit is shown on the right. The *arrow* symbol on the rectifier diagram indicates the direction of conventional current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

3.4. High-output X-ray Generators

A. Three-phase generators

❖ 3 phase power + full-wave rectification

→ 6 voltage pulses during each power cycle

- Voltage ripple: 13% ~ 25%
- Slight delay in phase b.t. waveforms → reduce ripple to 3% ~ 10%

B. Constant potential Generators

❖ 3-phase line voltage coupled directly to the high-voltage transformer

- ripple of less than 2%

→ high x-ray output per mAs, expensive

C. High-frequency Generators

❖ State of the art generator

❖ DC → high Freq. low Volt. AC → high Volt. AC

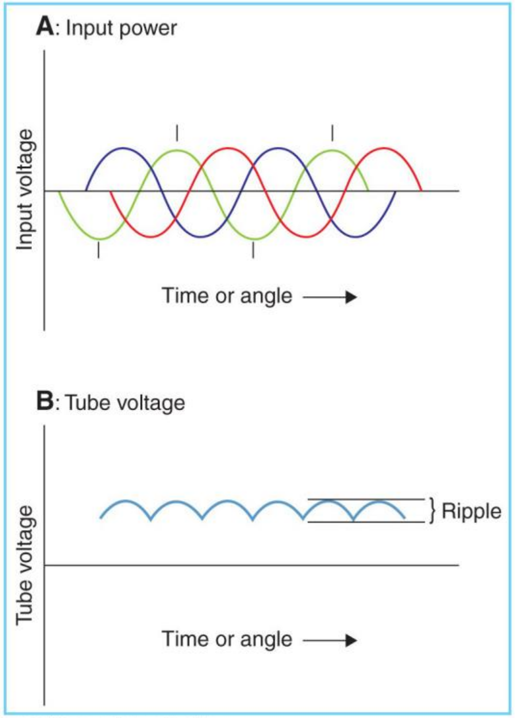


Figure 3.6. Voltage waveforms in a three-phase generator.

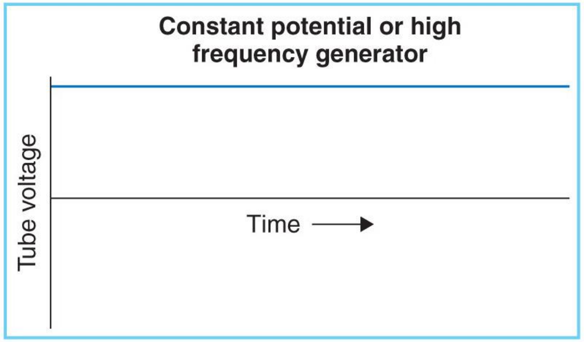


Figure 3.7. Voltage waveforms in a high-frequency generator.

Chapter

4

Clinical Radiation Generators

March, 2020

Ui-Jung Hwang, PhD, KBMP, DABR
Chungnam National University Hospital

Accelerators

Quality of X-ray depends on the applied Voltage (Beam penetration)

❖ **Kilovoltage Unit**:

- 20 kV: Grenz-Ray therapy (no longer used in RT)
- 40-50 kV: Contact therapy (SSD 2 cm)
- 50-150 kV: Superficial therapy (SSD 15-20 cm)
- 150-500 kV: Orthovoltage therapy
- 500 –1000 kV: Supervoltage therapy

❖ **Megavoltage Unit**: > 1 MV

ex: Van de Graaff generator,

Linear accelerator,

betatron

microtron,

Cyclotron, Synchrotron

teletherapy γ-ray unit (Co 60)

Electrostatic field type

(KE of the particle can not be larger then the applied potential E)

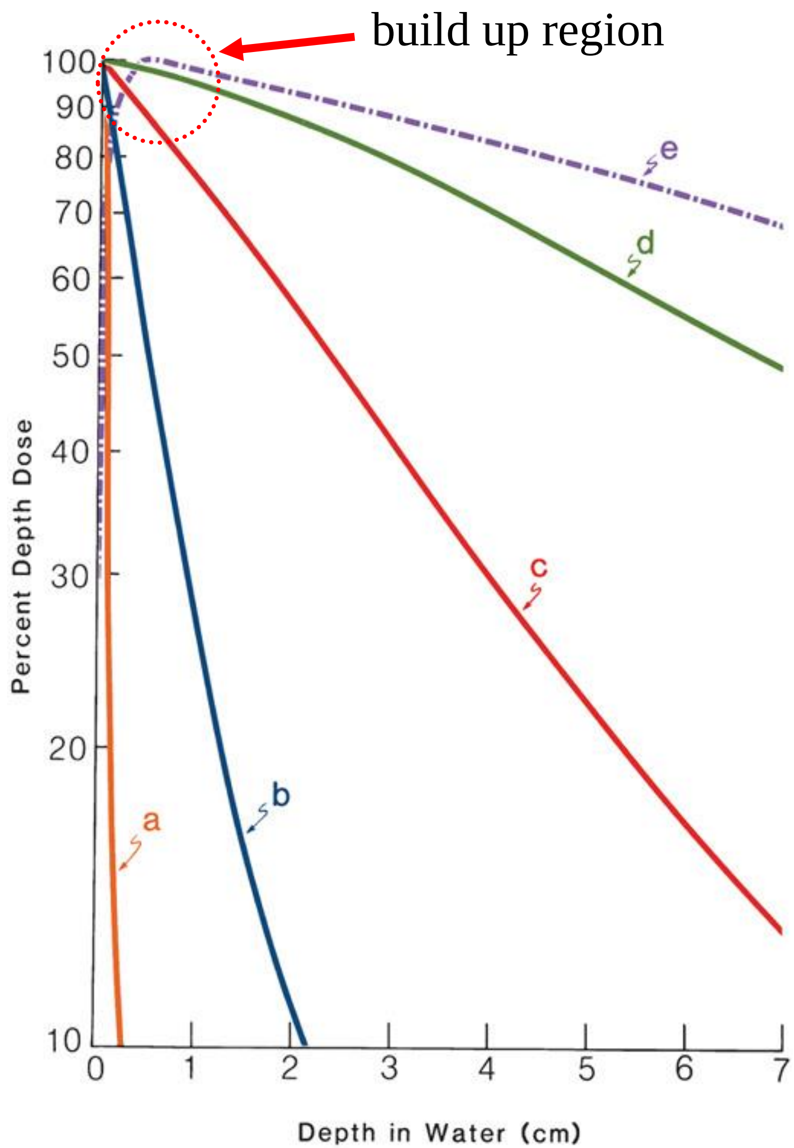
Cyclic type

Non conservative E field, but can produce charged particles of much higher KE than electrostatic accelerators.

→ uses variable EM field.

- Particles are made to follow a closed path of E(with M) field many times, then the KE >PE can be obtained.

Depth Dose Characteristics of X-rays



a: Grenz-ray Therapy

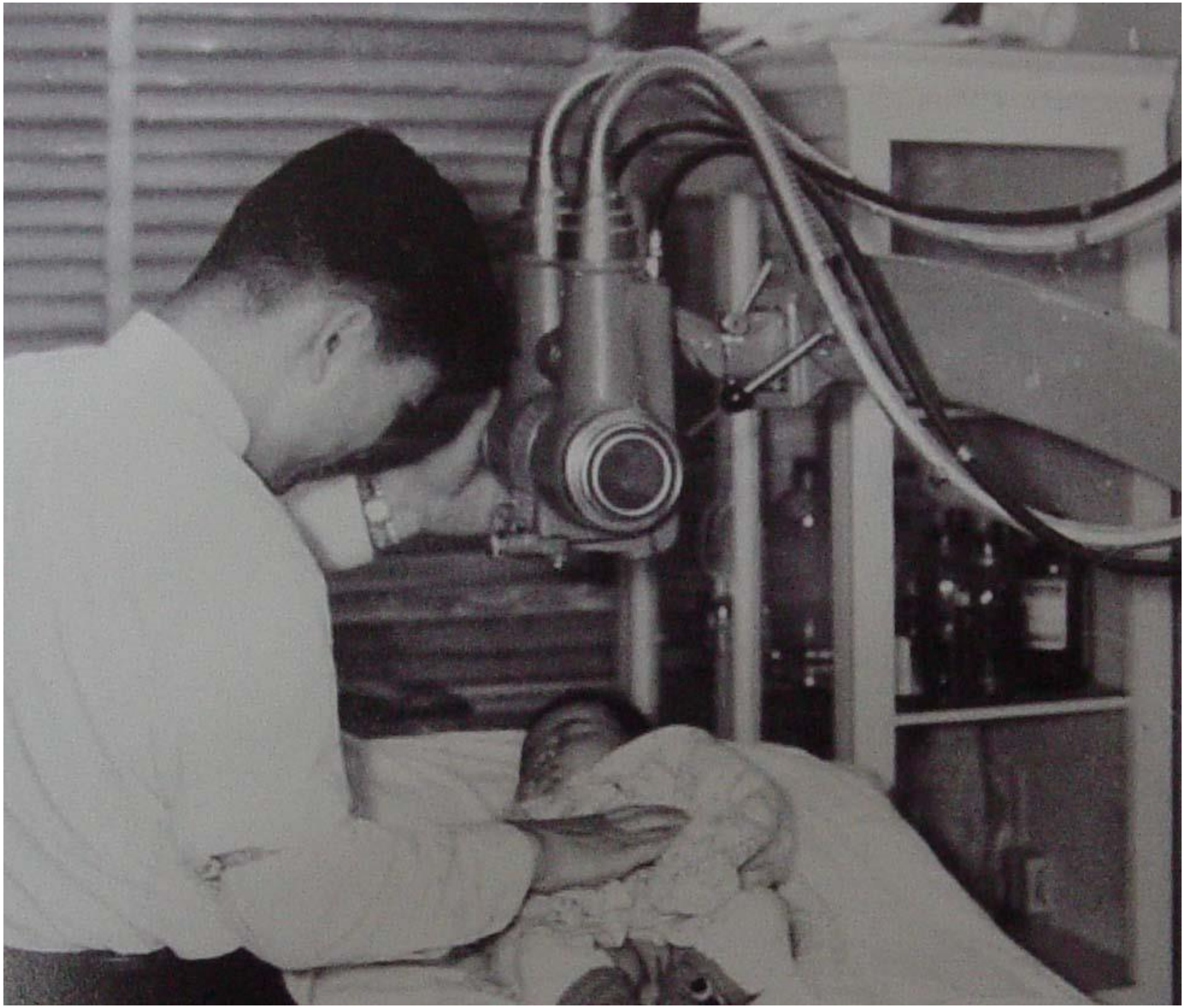
b: Contact therapy

c: Superficial therapy

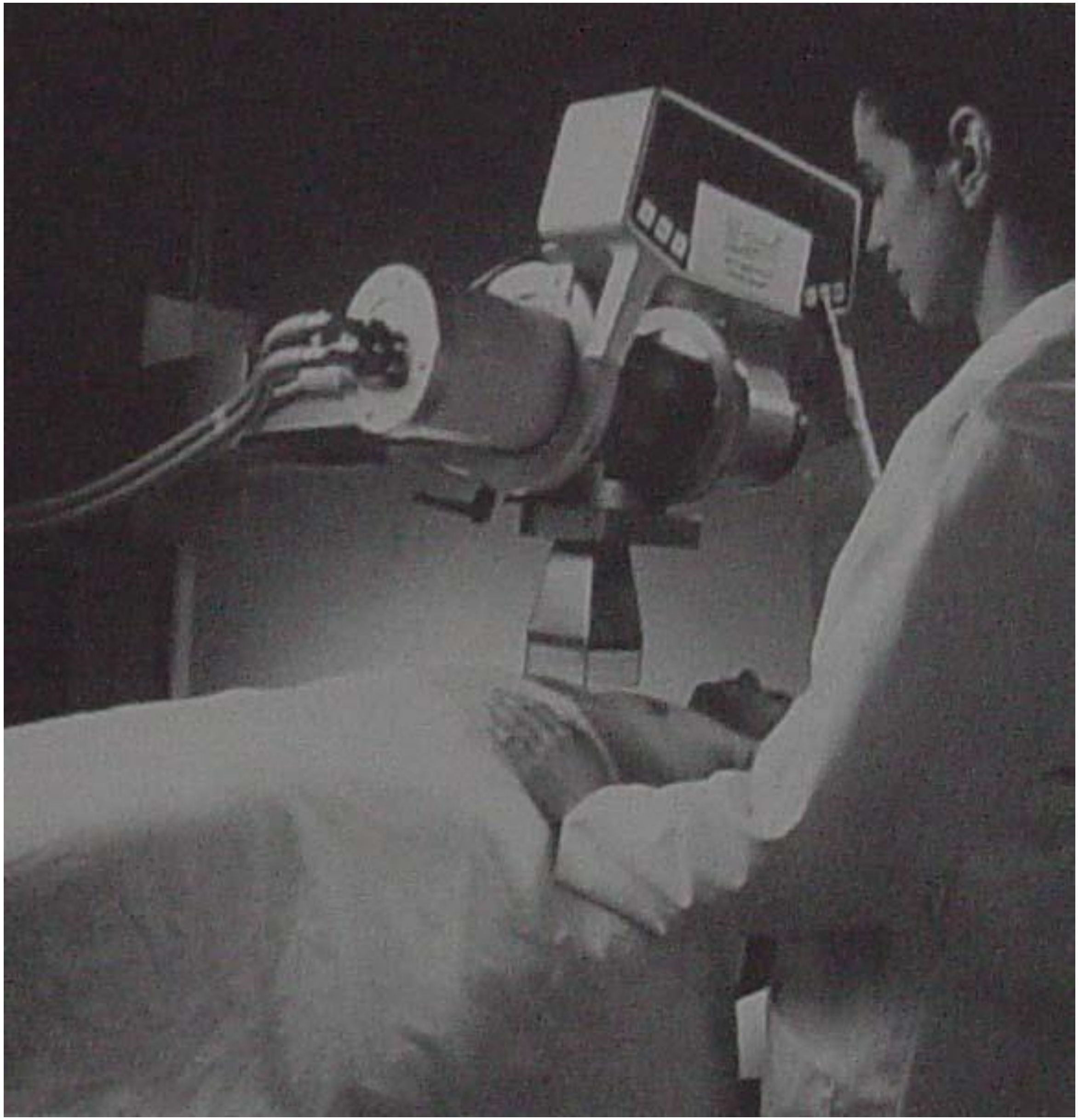
d: Orthovoltage therapy

e: Co-60

Figure 4.1. Depth dose curves in water or soft tissues for various quality beams. **Line a:** Grenz rays, half-value layer (HVL) = 0.04 mm Al, field diameter 33 cm, source to surface distance (SSD) = 10 cm. **Line b:** Contact therapy, HVL = 1.5 mm Al, field diameter = 2.0 cm, SSD = 2 cm. **Line c:** Superficial therapy, HVL = 3.0 mm Al, field diameter = 3.6 cm, SSD = 20 cm. **Line d:** Orthovoltage, HVL = 2.0 mm Cu, field size = 10 × 10 cm, SSD = 50 cm. **Line e:** Cobalt-60 γ rays, field size = 10 × 10 cm, SSD = 80 cm. (Plotted from data in Cohen M, Jones DEA, Green D, eds. Central axis depth dose data for use in radiotherapy. *Br J Radiol.* 1978[suppl 11]. The British Institute of Radiology, London, with permission.)



120 kVp - 원자력병원



Orthovoltage x-ray unit (200-300 kV)

4.2. Van de Graaff generator

- typically 2 MV (~10 MV)
- 20 ~ 40 kV is applied across a moving belt
- corona discharge and spread electrons to the belt
- Insulation by N_2 and Co_2 gas of 20 atm
- no longer used because of emergence better machines such as Co-60 unit and LINAC

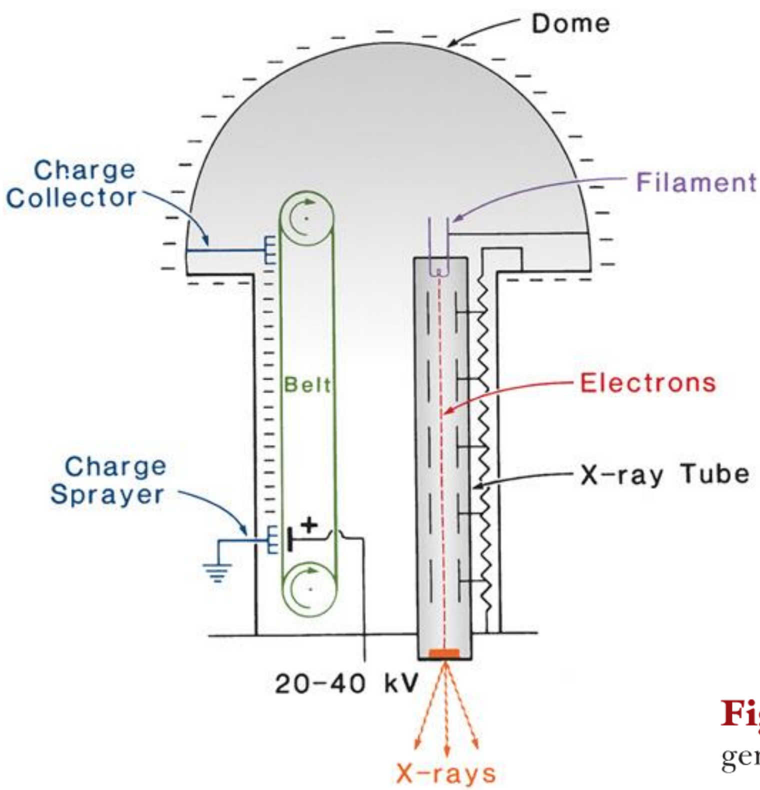
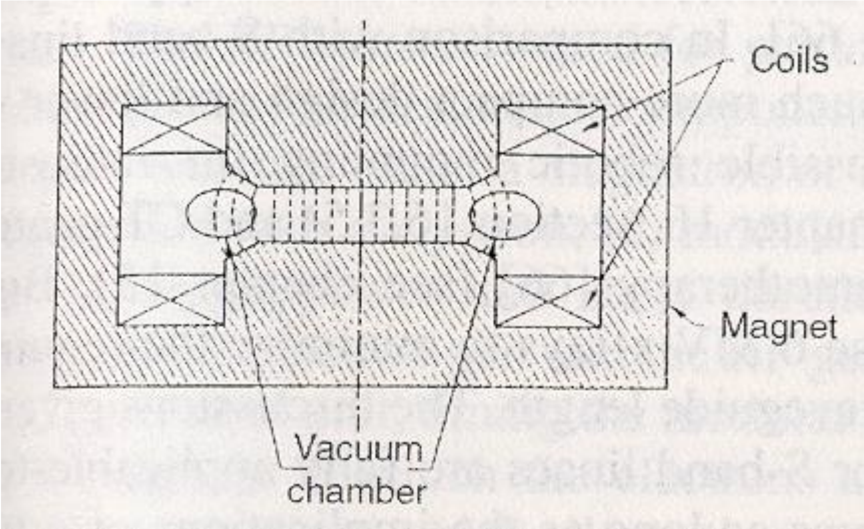


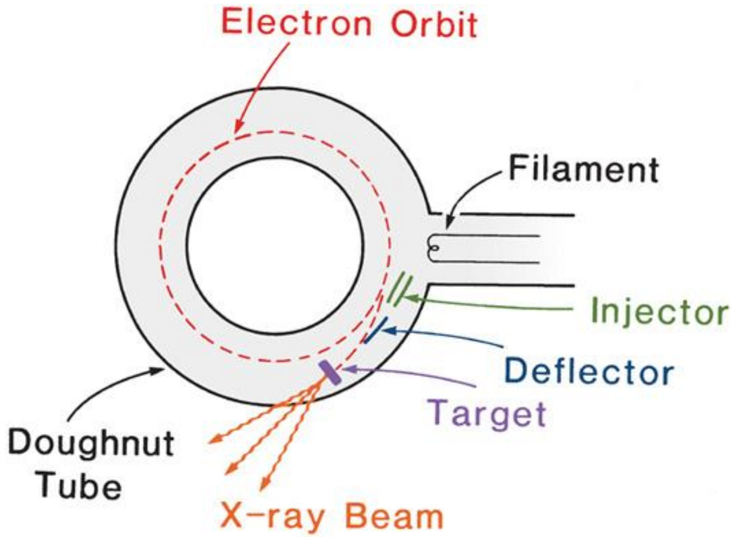
Figure 4.4. A Van de Graaff generator.

Betatron

- ❖ Developed in 1940 by D.W. Kerst as a cyclic electron accelerator for basic physics research.
- ❖ Consists of a magnet fed by an AC of 50-200Hz.
- ❖ Electrons are made to circulate in a toroidal vacuum chamber which is placed into the gap bw two magnet poles.
- ❖ electrons are accelerated by the E field, which is induced in the donut by the changing magnetic flux in the magnet.
- ❖ 1950's betatron plays an important role in MV RT.
- ❖ Linac is superior to betatron
  - higher output, larger FS, more compact design, quieter operation **EXCEPT** the lower cost for **e** beam
- ❖ **Only used to accelerate electrons.**

Betatron


Coils
Magnet
Vacuum chamber


Electron Orbit
Filament
Injector
Deflector
Target
Doughnut Tube
X-ray Beam

Cyclotron

•Developed in 1930 by E.O. Lawrence for acceleration of ions (protons, deutrons, heavier ions) to a KE of a few MeV.

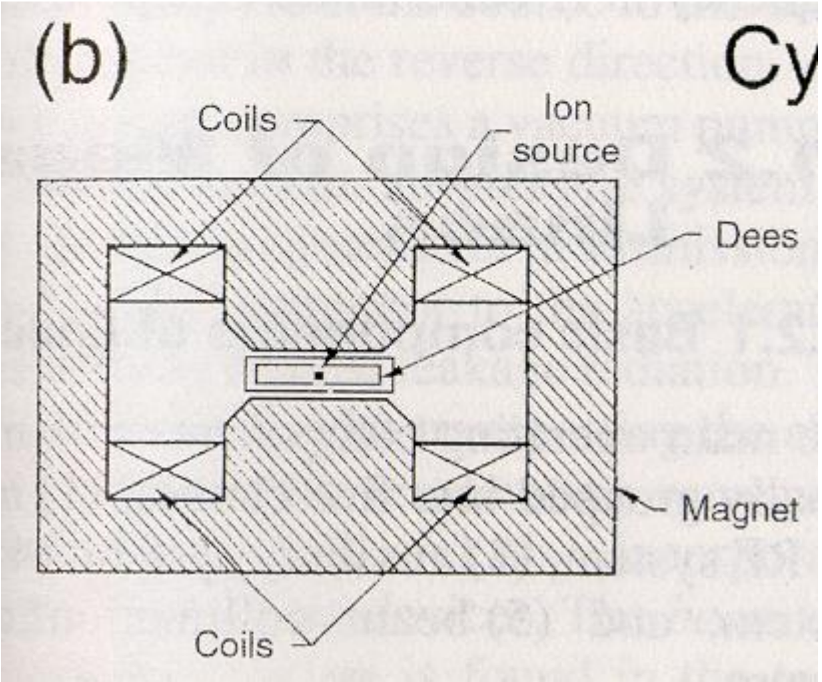
•Developed for basic research of physics, but found to be useful for radiotherapy with **proton and neutron beams**.

•Particles are accelerated along a spiral trajectory guided inside two evacuated half-cylindrical electrodes (dees) by a uniform magnetic field (~1T).

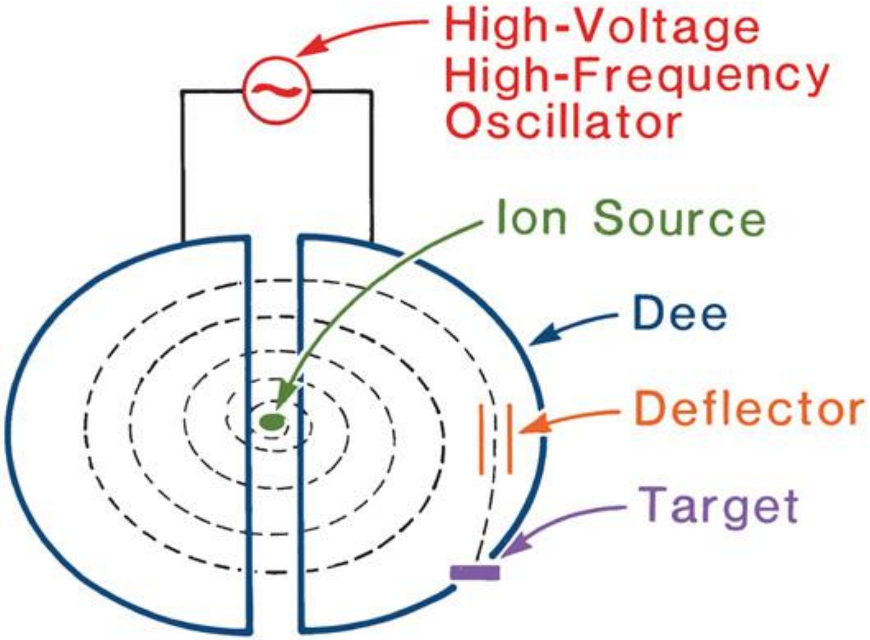
•With constant frequency (10-30MHz) voltage is applied bw the two electrodes.→ charged particles are accelerated while crossing the gap bw the electrodes.

• Can not be used for electron because of the increased relativistic effects. (V is not constant & not in phase with RF fields)

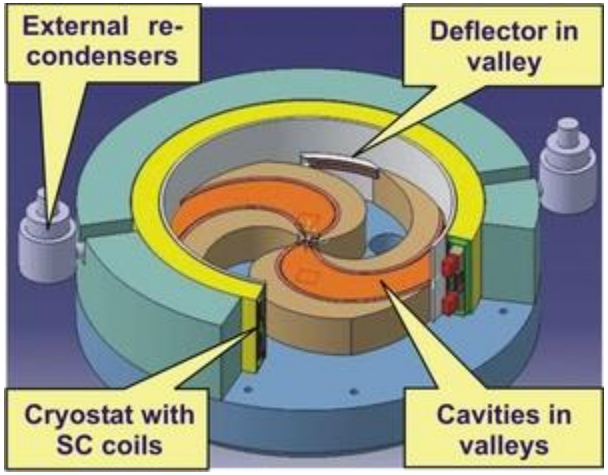
Cyclotron



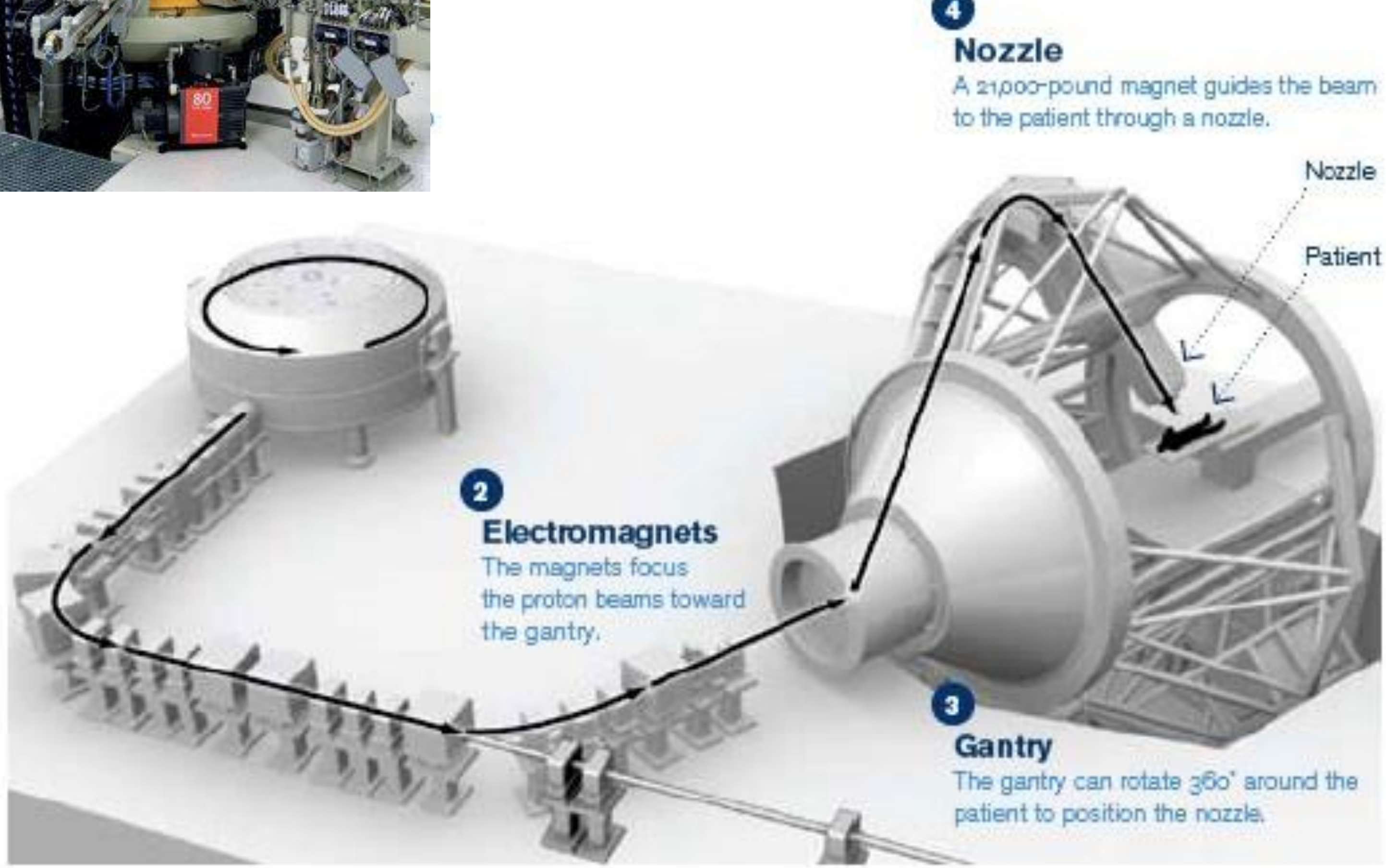
(b)
Cy
Coils
Ion source
Dees
Magnet
Coils



High-Voltage High-Frequency Oscillator
Ion Source
Dee
Deflector
Target



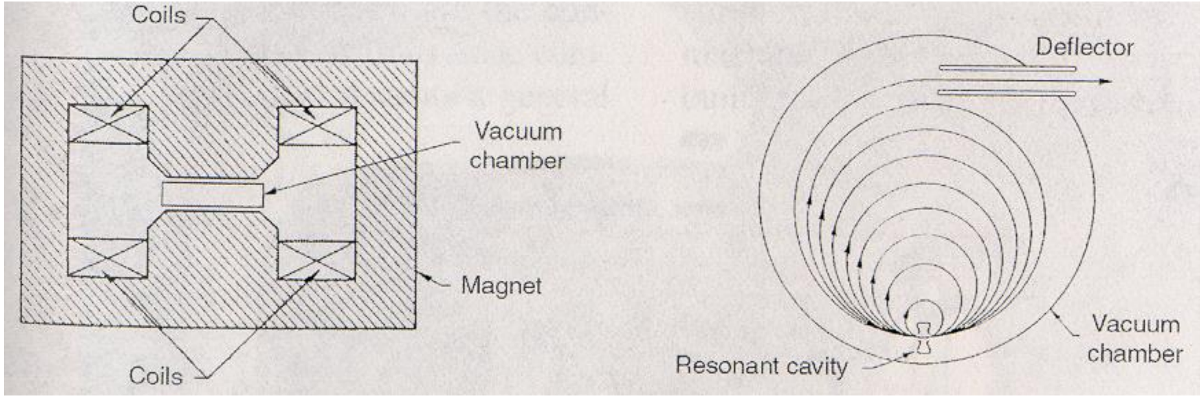
External re-condensers
Deflector in valley
Cryostat with SC coils
Cavities in valleys


4
Nozzle
A 21,000-pound magnet guides the beam to the patient through a nozzle.
Nozzle
Patient
2
Electromagnets
The magnets focus the proton beams toward the gantry.
3
Gantry
The gantry can rotate 360° around the patient to position the nozzle.

Microtron

- Electron accelerator : combined feature of linac &cyclotron.
- Developed in 1944 by V.I. Veksler. Used contemporary **photon & electron radiotherapy**.
- Two types: circular & racetrack.
- Circular: electrons gain energy from a microwave resonant cavity and describes circular orbit with increasing radius in uniform magnetic field.
- Advantage of microtron over linac:
  - smaller beam divergency
  - less energy spread in the electron beam spectrum.
- Simplifies the beam transport from vacumm chamber to the x-ray target and facilitates the use of multiple beamlines.
- Several treatment rooms can be designed to share one microtron

Microtron



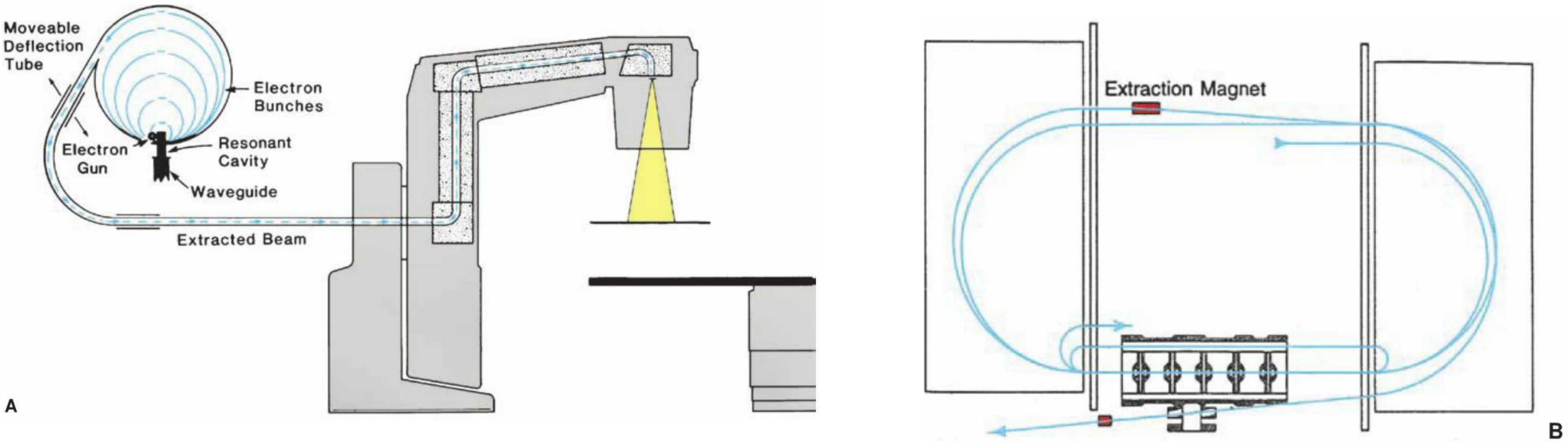


Figure 4.11. **A:** Schematic diagram of a circular microtron unit. (Reprinted with permission from AB Scanditronix, Uppsala, Sweden.) **B:** Electron orbits and accelerating cavities in a racetrack microtron. (From Karzmark CJ, Nunan CS, Tanabe E. *Medical Electron Accelerators*. New York: McGraw-Hill, 1993; with permission.)

Synchrotron

❖ Like betatron, charged particles follow a circular orbit of constant radius in the form of donut.

❖ The donut is placed into a magnetic field that changes in time to account for the increase in particle mass with energy.

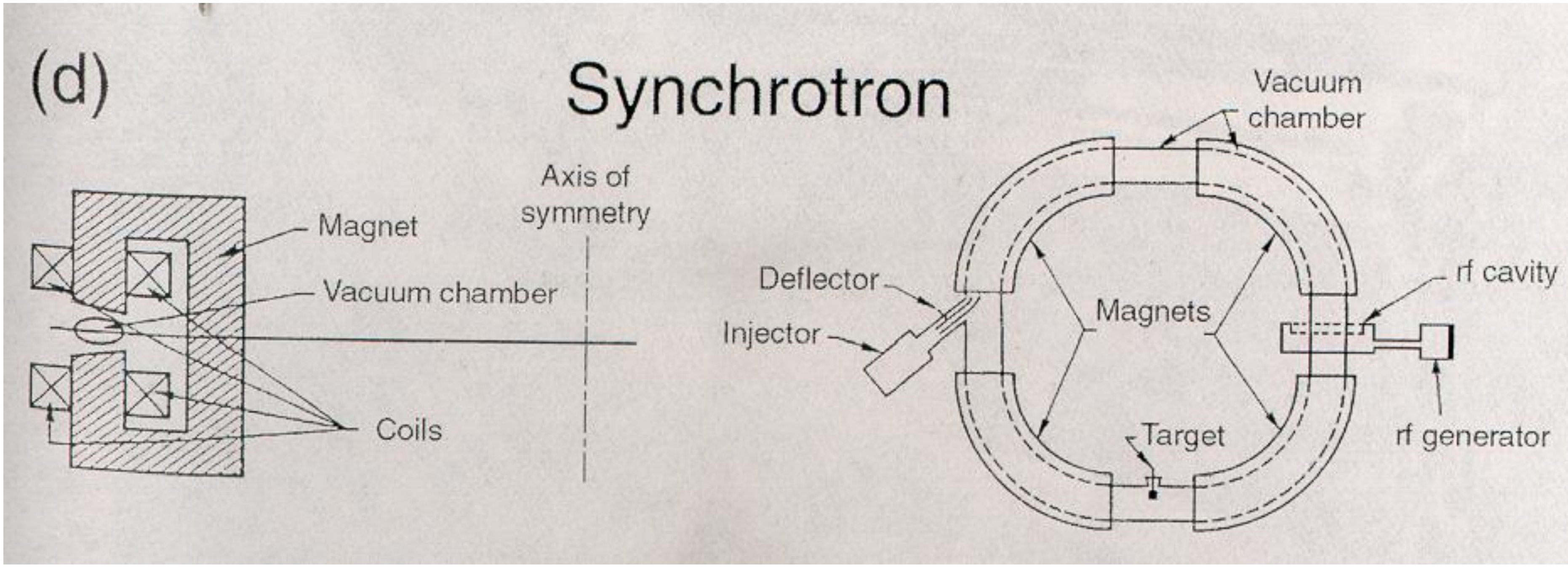
❖ The particles are accelerated by an RF electric field localized at a certain point.

~ MHz for protons, ~100 MHz for electrons.

❖ Mainly used for high energy particle physics research, but are also used as source for **proton beam radiotherapy.**

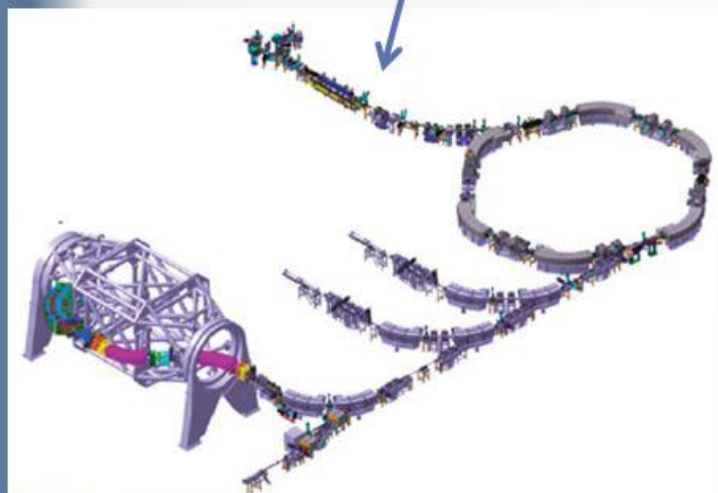
❖ Need auxiliary accelerator as a injector.

Synchrotron

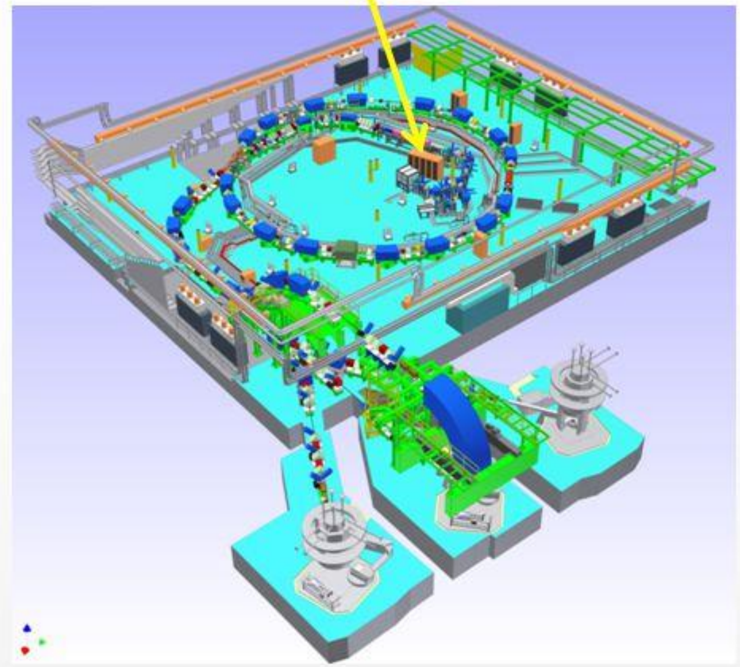


Synchrotron facility layout: Injector

The injector is placed outside the ring for easier maintenance or inside to save space



HIT (Heidelberg, Germany)



CNAO (Pavia, Italy)

Linear Accelerators

Historical development of Linacs.

❖ Linac development: More gradual

❖ 1935-1945: the development and basic theoretical understanding of microwave device was achieved through the invention of microwave cavities and microwave power sources(microtron & klystron).

❖ 1945-1960: various physics research groups built linacs.

– W.W. Hansen's group (Stanford Uni.USA)

- D.D. Fry's group (TRE in England)

❖ 1947 : Stanford: 4.5 MeV electron energy

TRE: 3.5 MeV electron energy

- ❖ 1952, Ginzton, Hansen, and Chodorow (Stanford Univ.) built a 30 MW klystron. → High energy linac & very compact linac in the 10-25 MeV energy range.
- ❖ The first clinical linac: early 1950's. Hammersmith hospital in London (England) – 8MV x-ray beam with 2MW magnetron
- ❖ 5 MV linac using 1 MW klystron was built and installed in Stanford & treated the first patient in January 1956
- ❖ Varian : The first North American company to build a commercial medical linac. 1962 built the first prototype fo 6MV isocentric linac. Now x-ray energy 4-25 MV

Basic description of medical linacs

❖ Cyclic accelerator which accelerate electrons to kinetic E from 4 to 25 MeV

❖ Using non-conservative microwave RF

- frequency range: 10^3.MHz(L band) to 10^4 MHz(X band)

- vast majority running at 2586 MHz(S band).

❖ Electrons are accelerate following straight trajectory (accelerating waveguides)

❖ High power RF field are produced through the decelerating electrons in retarding potentials in magnetron and klystron.

Radio Frequency (RF) is a rate of oscillation of electromagnetic waves in the range of about 30 kHz to 300 GHz. Frequency Ranges of Microwaves = 300 MHz to 300 GHz.

Frequency Range	Microwave / Radar Bands
216 — 450 MHz	P-Band
1 — 2 GHz	L-Band
2 — 4 GHz	S-Band
4 — 8 GHz	C-Band
8 — 12 GHz	X-Band
12 — 18 GHz	K_u-Band
18 — 26.5 GHz	K-Band
26.5 — 40 GHz	K_a-Band
30 — 50 GHz	Q-Band
40 — 60 GHz	U-Band
50 — 75 GHz	V-Band
60 — 90 GHz	E-Band
75 — 110 GHz	W-Band
90 — 140 GHz	F-Band
110 — 170 GHz	D-Band
110 — 300 GHz	mm-Band

Bands for RF Accelerators

IEEE US Bands

30 - 300 kHz : LF-band
300 - 3000 kHz : MF-band
3 - 30 MHz : HF-band
30 - 300 MHz : VHF-band
300 - 1000 MHz : UHF-band

American / European Frequencies

S-band : 2856 MHz / 2998 MHz
C-band : 5712 MHz / 5996 MHz
X-band : 11424 MHz / 11992 MHz

5 Generation of Linacs.

1) Low-energy photons(4-8 MV)

Straight-through beam; fixed flattening filter; external wedges; symmetric jaws; single transmission ionization chamber; isocentric mounting

2) Medium-energy photons (10-15 MV) and electrons

Bent beam; movable target and flattening filter; dual transmission ionization chamber; electron cones

3) High-energy photons (18-25 MV) and electrons

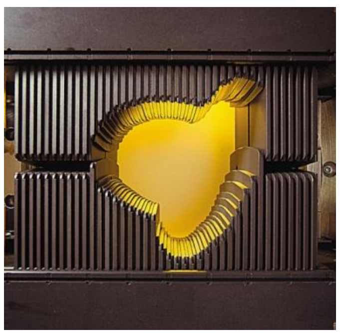
Dual photon energy and multiple electron energies; achromatic bending magnet; dual scattering foils or scanned electron pencil beam; automatic wedge selector; independent collimator jaws

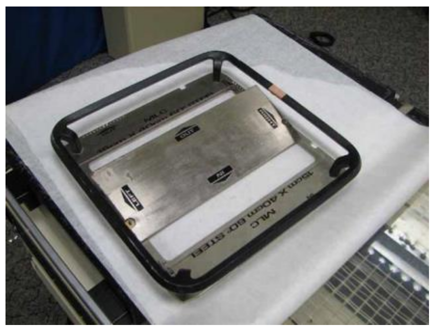
4) High energy photons and electrons.

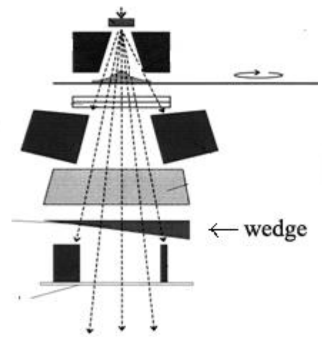
Computer-controlled operation; dynamic wedge; electronic portal imaging device; multileaf collimator.

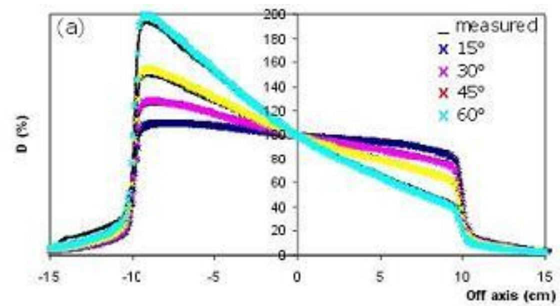
5) High energy photons and electrons

Photon beam intensity modulation with MLC. Full dynamic conformal dose delivery with intensity modulated beam produced with an MLC









Linac: Choice of **S band**-the most practical compromise bw the required accelerating waveguide dimensions and dimensional tolerances governed by the manufacturing process and thermal expansion during operation.

X-band (10^4 MHz) linac: cyberknife (9300 MHz)

S band: Tomotherapy (3GHz)

Design of Megavoltage Linacs

1. **Basic component**

1) Injection system: source of electron-electron gun

2) RF system: that used for particle acceleration

- RF power source (magnetron or RF driver with klystron)
- Modulator: generation of high power & short duration of pulse.
- control unit: timing the modulator
- Wave guide
- Circulator: allow the propagation of RF power (prohibit of reverse direction)

3) **auxiliary system:** vacuum pumping system, water cooling system, air pressure system, gas dielectric system for transmission of microwaves from the RF generator to wave guide. Shielding.

4) **beam transport system** transporting electron beam from waveguide to target/scattering foil, magnetic steering, focusing device.

5) **Beam collimation and monitoring system** located in the treatment head, provide shaping manipulating & monitoring of the x-ray/e beams.

Linear accelerator

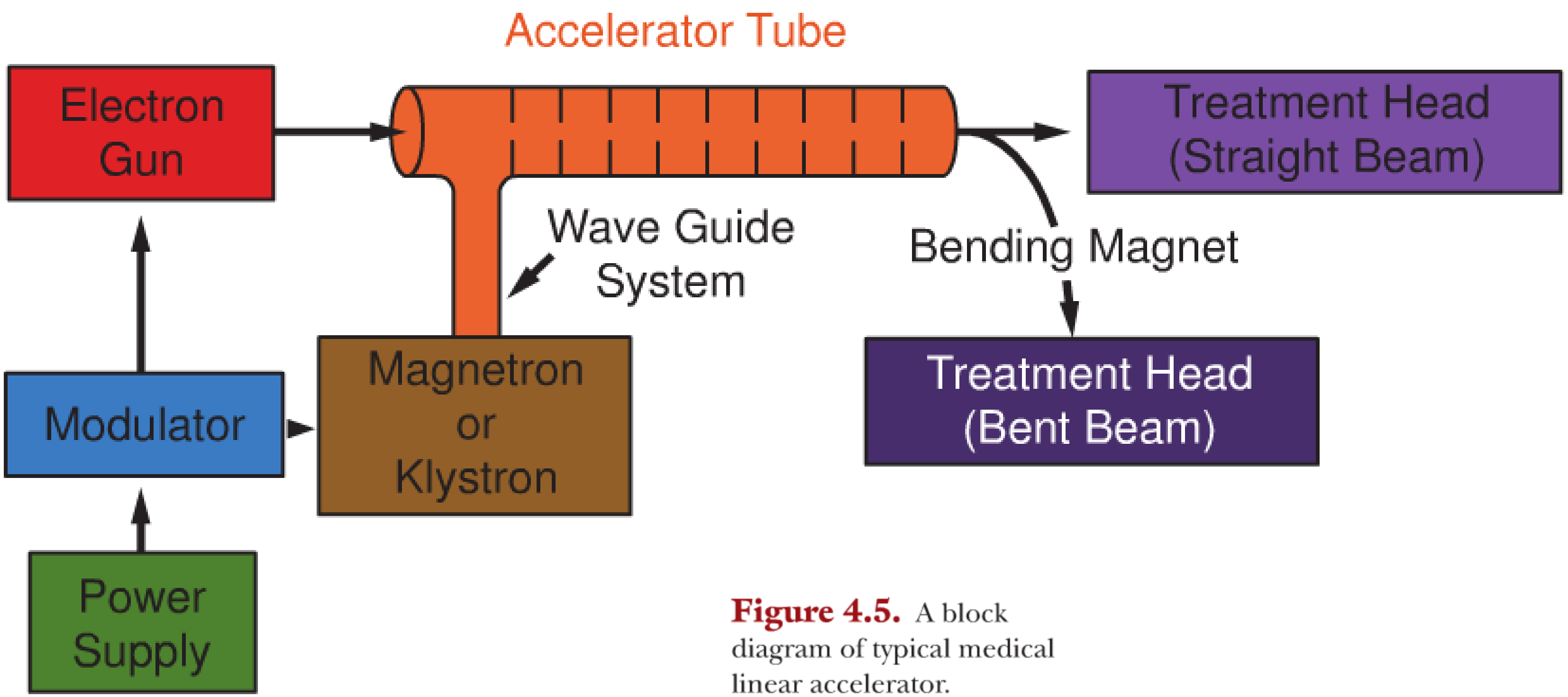
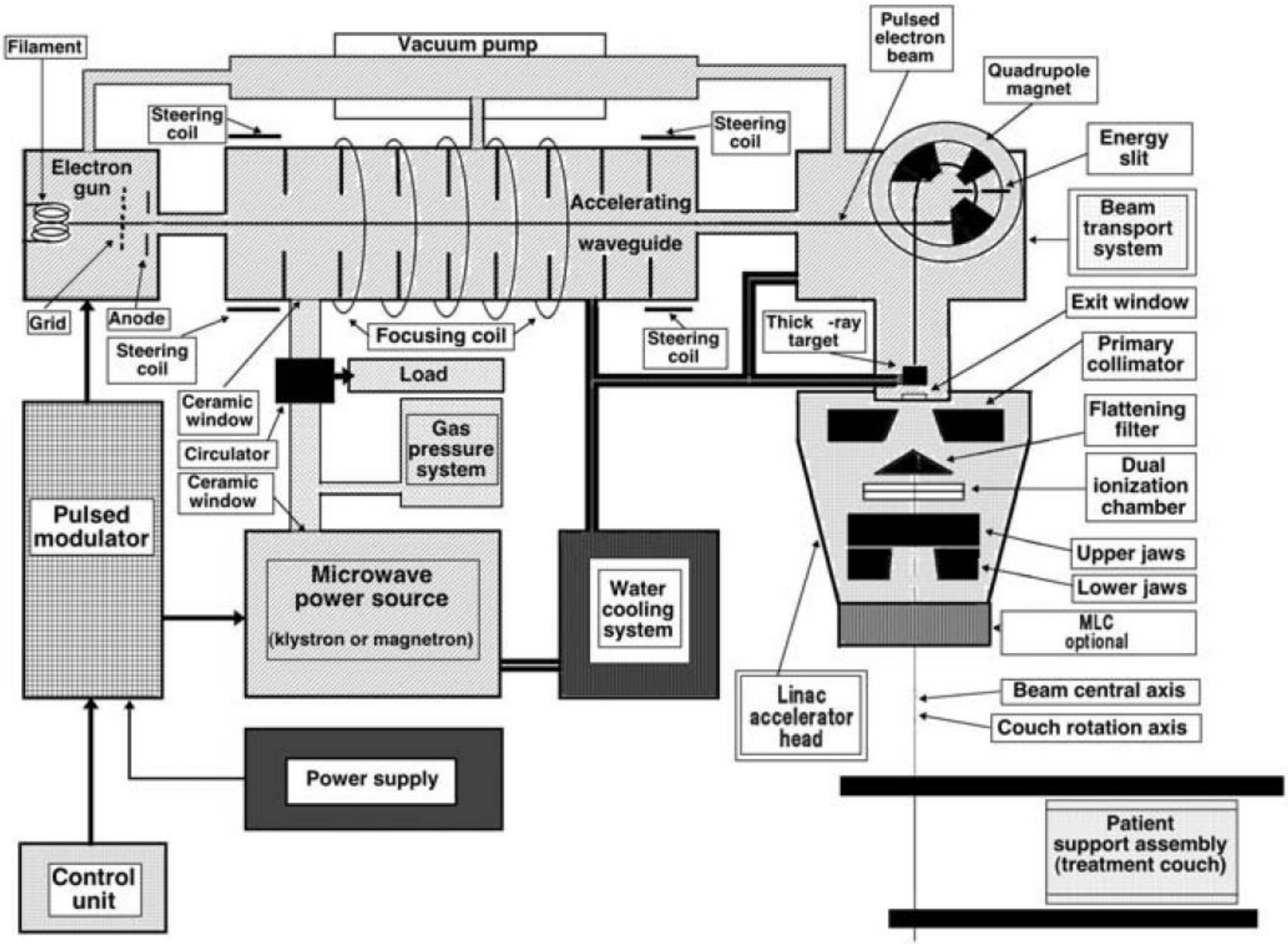


Figure 4.5. A block diagram of typical medical linear accelerator.

Linear accelerator



- Power supply provides DC power to the modulator,

  - which includes the pulse-forming network and a switch tube known as hydrogen thyratron

- Flat-topped high voltage DC pulse of a few microseconds in duration from the modulator

- These pulses are delivered to the magnetron or klystron and simultaneously to the electron gun

- Pulsed microwaves produced in the magnetron or klystron are injected into the accelerator tube via waveguide system

- At the proper instant, electrons, produced by an electron gun, are pulse injected into the accelerator structure

- Initial energy of electrons injected into: ~ 50 keV

- High-energy electrons from the exit window: in the form of a pencil beam of about 3 mm in diameter

RF power generation (Magnetron vs klystron)

A. Magnetron

- ❖ Produces microwave pulse of 3 GHz, microsecond duration, several hundred pulses per second repetition
- ❖ Vacuum diode tube with a cylindrical cathode surrounded with an anode. - symmetrical array of resonant cavities.
- ❖ Cavities oscillate in the fundamental mode(determined by the design dimension)
- ❖ Whole device immersed in a uniform magnetic field provided by poles of permanent magnet (static B-field + pulsed DC E-field)
- ❖ electron from cathode → accelerated to anode.
- ❖ Cavity → acceleration&deceleration → 60% of KE to microwave power
- ❖ Peak power → electron emission & Voltage b.t. cathode &anode.

  typically 2 MW (for 6 MV or less Linac)

  Max. 5 MW (for 25 MeV Linac)

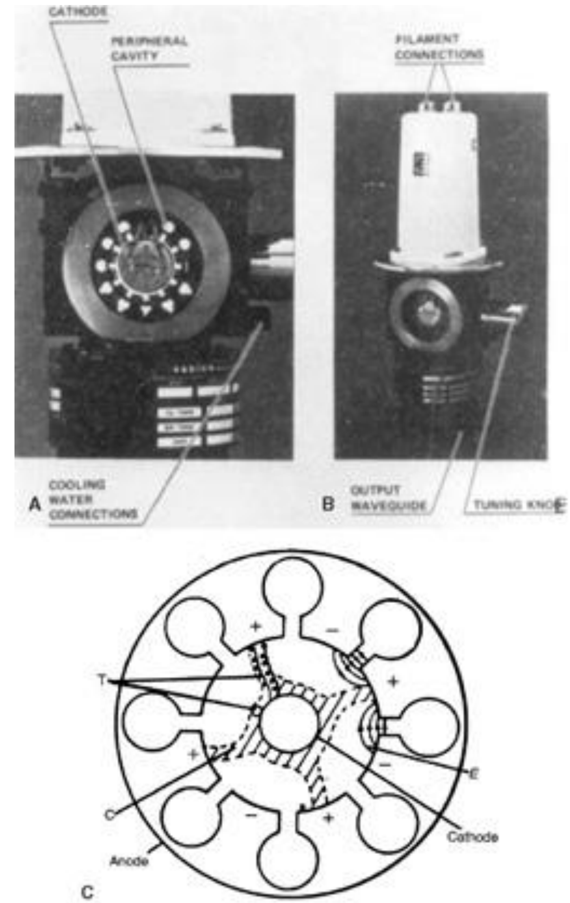
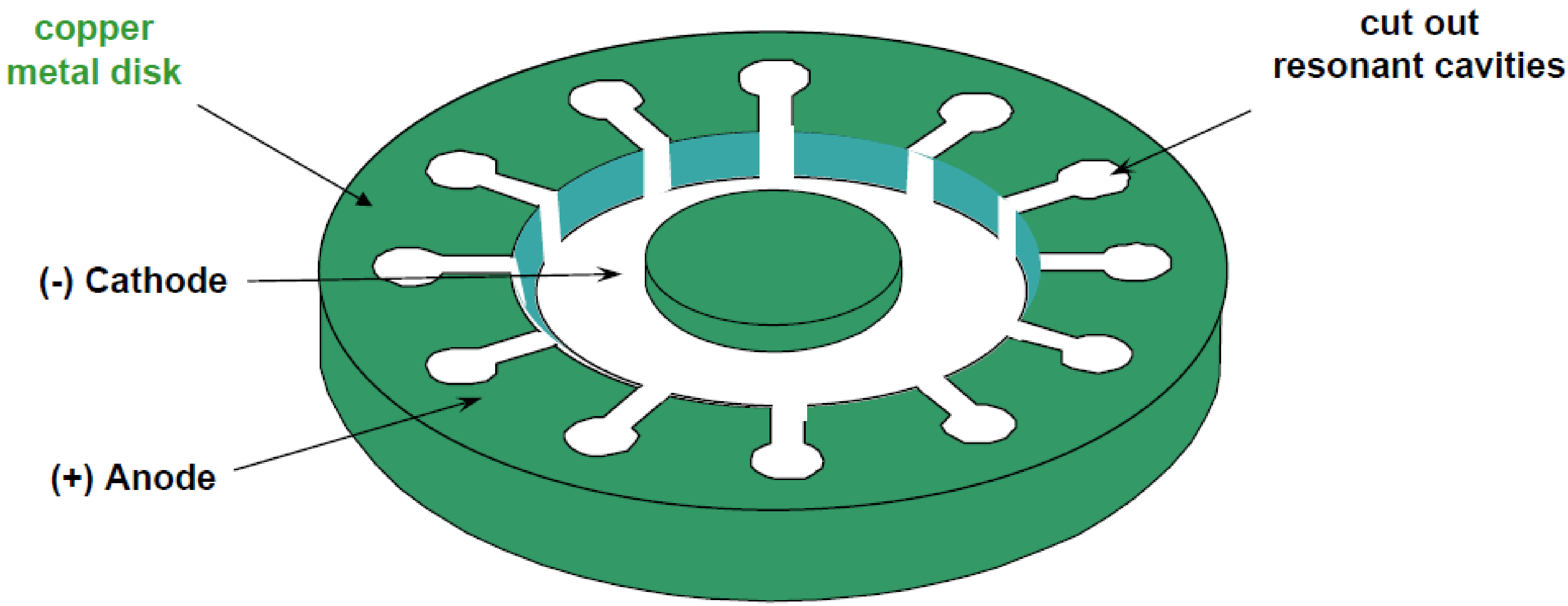


Figure 4.6. **A,B:** Cutaway magnetron pictures. **C:** Cross-sectional diagram showing principle of magnetron operation. (From

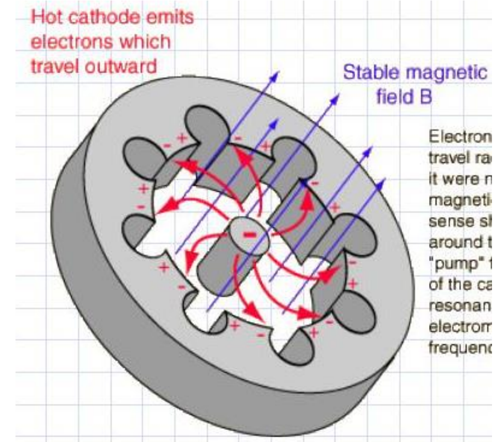
Magnetron

The magnetron is made from a solid copper metal disk
in which resident cavities have been cut out.



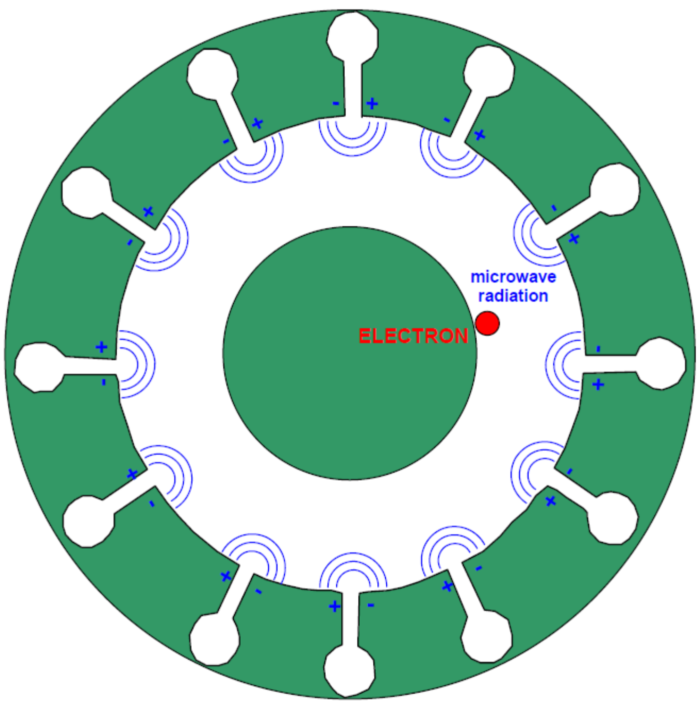
At the center of the disk is a cathode and the outer rim is the anode.

Magnetron



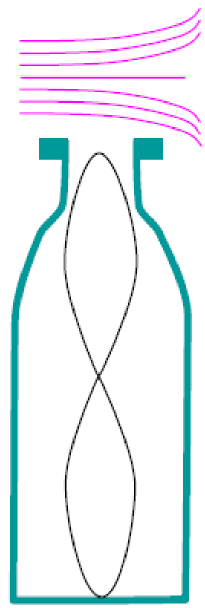
which shows an electron spiraling in to the anode generating microwave radiation.

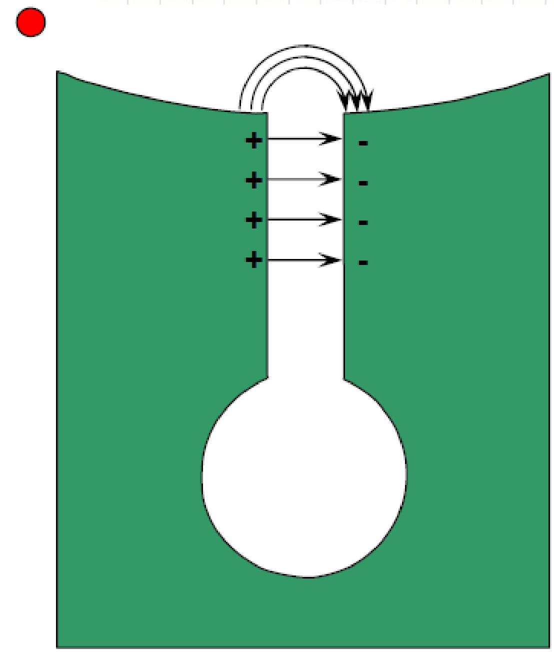
just like the wind blowing past a bottle the resonant cavity will generate an oscillating vibration in the cavity.



IU

bottle





This oscillation will be in the frequency range of microwave radiation based on the dimensions of the cavity.

Klystron

❖ Not a generator of microwaves but rather a microwave amplifier
❖ Driven by low-power microwave oscillator
❖ Velocity modulation to form electron bunching through drift tube
  - electron acceleration & deceleration
❖ Max power 7 MW or higher
❖ Electrons are accelerated toward ground cavity (- Voltage pulse applied).
❖ pulse from the modulator accelerate electrons pass through two resonant cavities.
  - buncher cavity: excited by low-power oscillator (Rf driver)
  - catcher cavity: emit high power RF

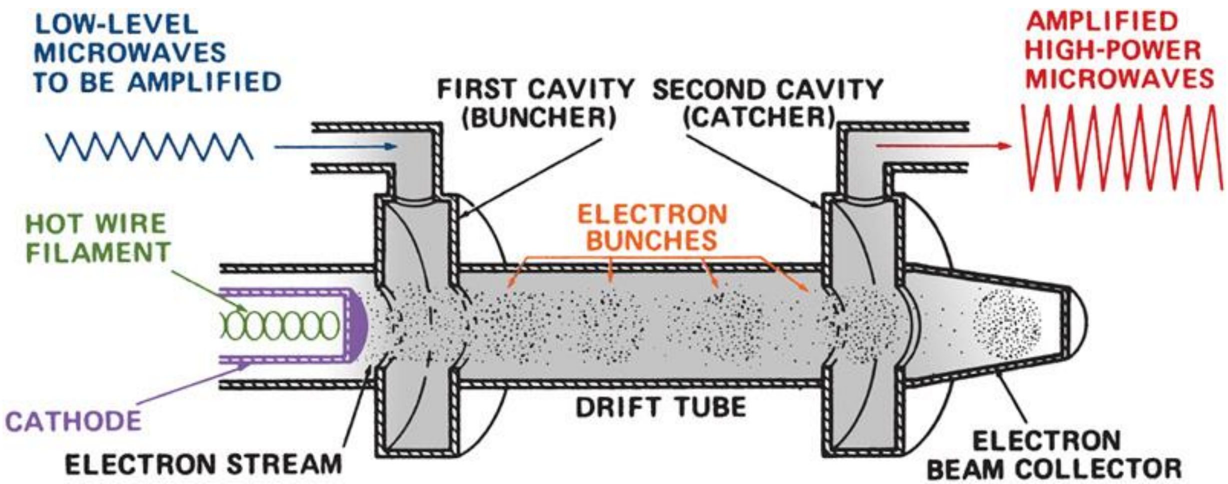
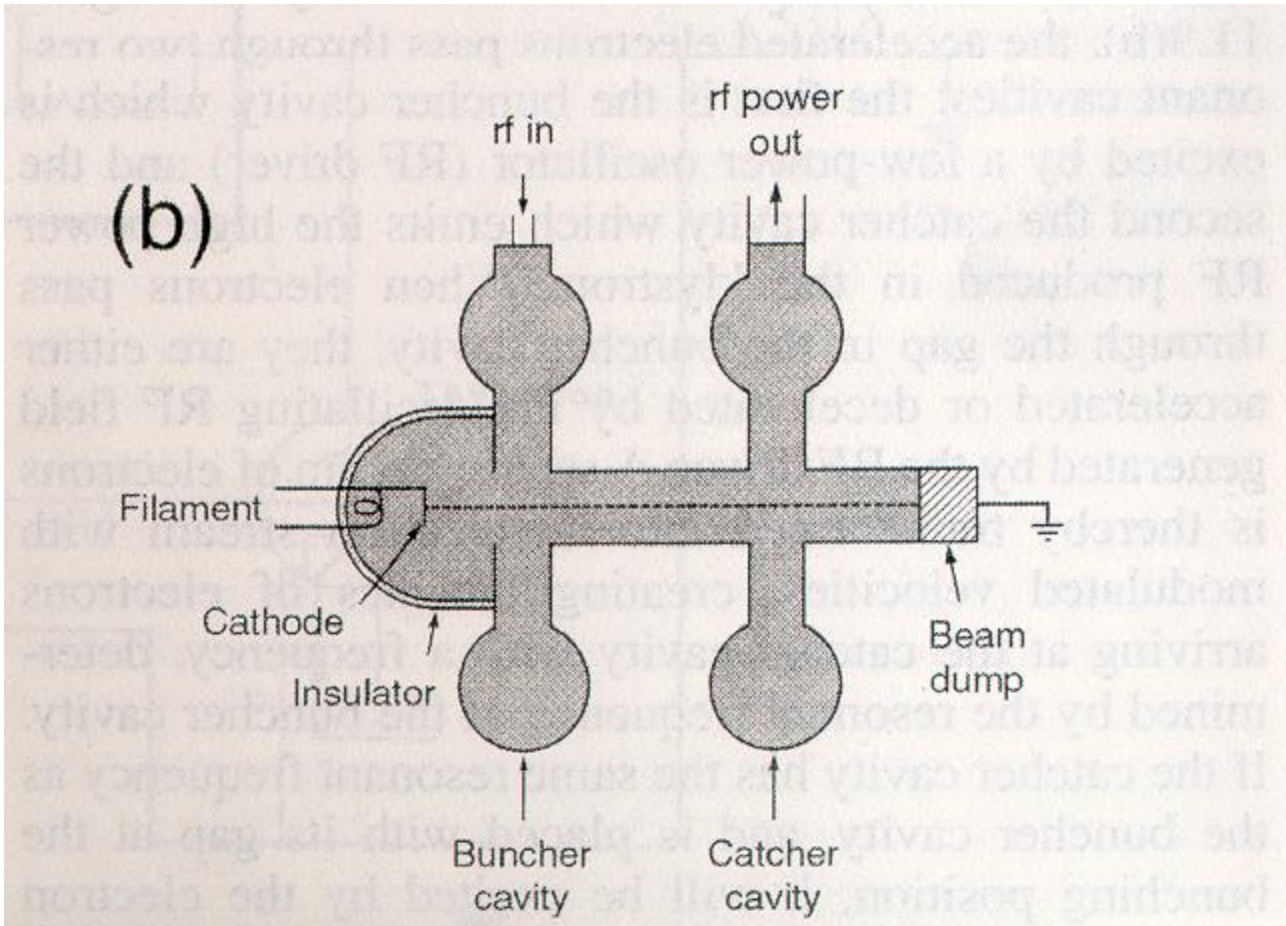


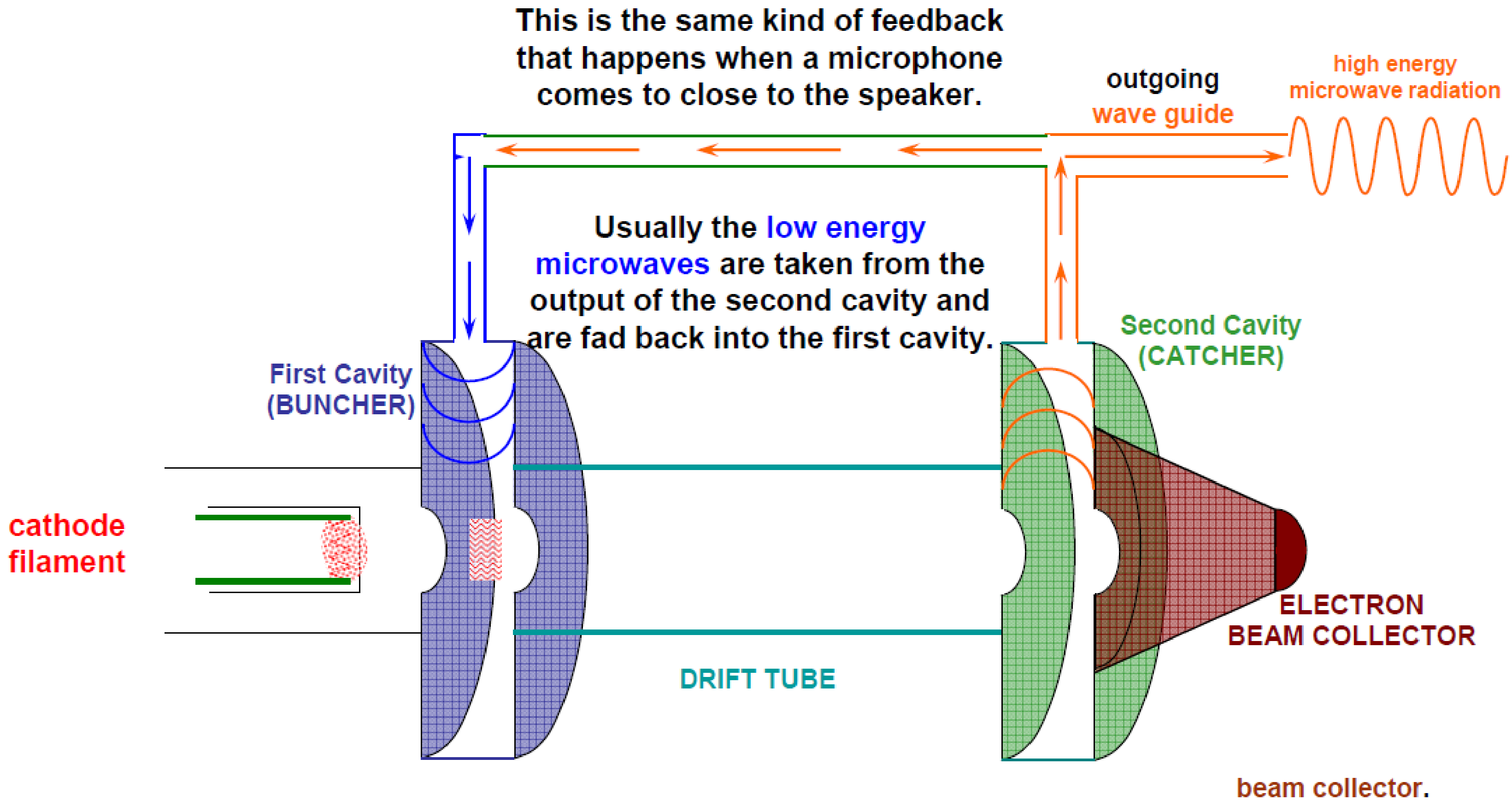
Figure 4.7. Cross-sectional drawing of a two-cavity klystron. (From Karzmark CJ, Morton RJ. *A Primer on Theory and Operation of Linear Accelerators in Radiation Therapy*. Rockville, MD: U.S. Department of Health and Human Services, Bureau of Radiological Health; 1981, with permission.)

Klystron



(b)
rf in
rf power
out
Filament
Cathode
Insulator
Buncher
cavity
Catcher
cavity
Beam
dump

Klystron


This is the same kind of feedback that happens when a microphone comes to close to the speaker.
outgoing wave guide
high energy microwave radiation
Usually the low energy microwaves are taken from the output of the second cavity and are fad back into the first cavity.
First Cavity (BUNCHER)
Second Cavity (CATCHER)
cathode filament
ELECTRON BEAM COLLECTOR
DRIFT TUBE
beam collector.

Magnetron vs Klystron

❖ Magentron

- smaller in size , no RF driver, with lower voltage, lower price.
- less stable, low power

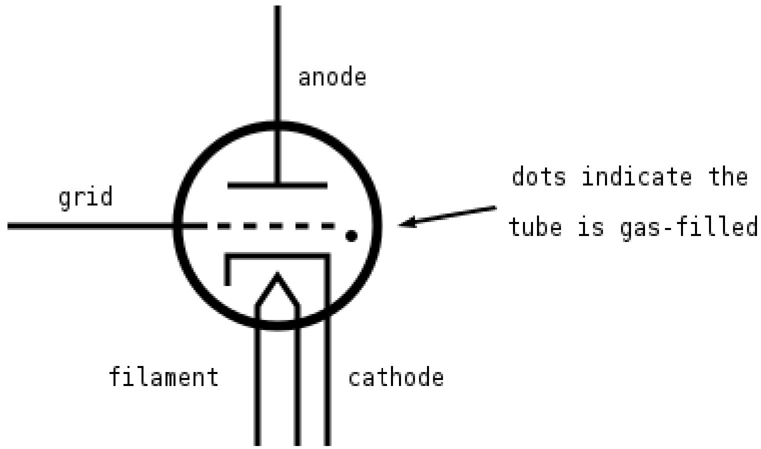
❖ Klystron

- Generally used for high E, > 5MW
- Bulky, need higher voltage, need RF driver, should be in a insulating oil tank

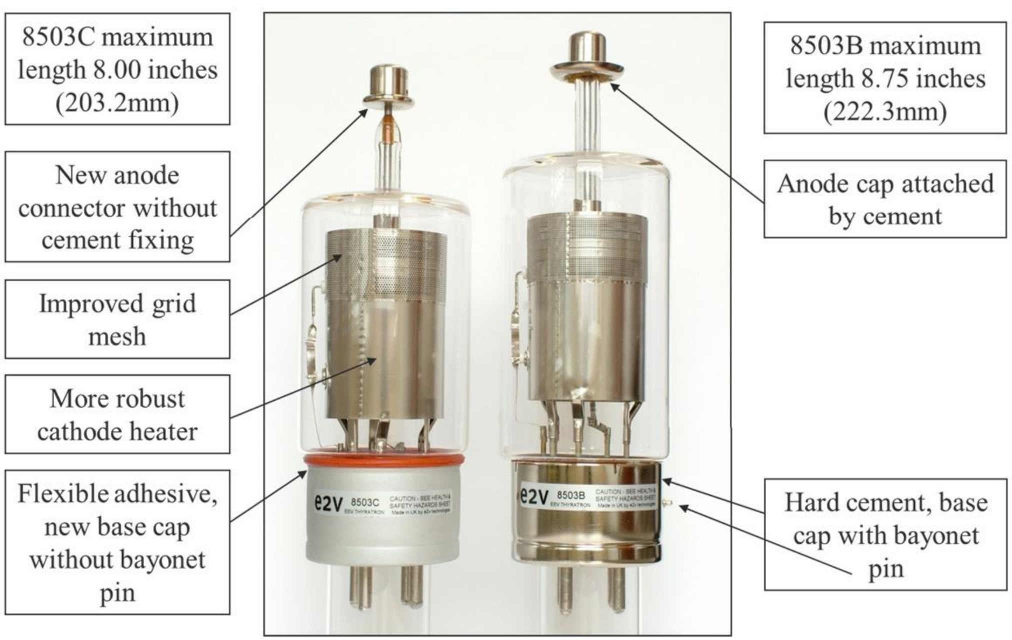
Thyratron

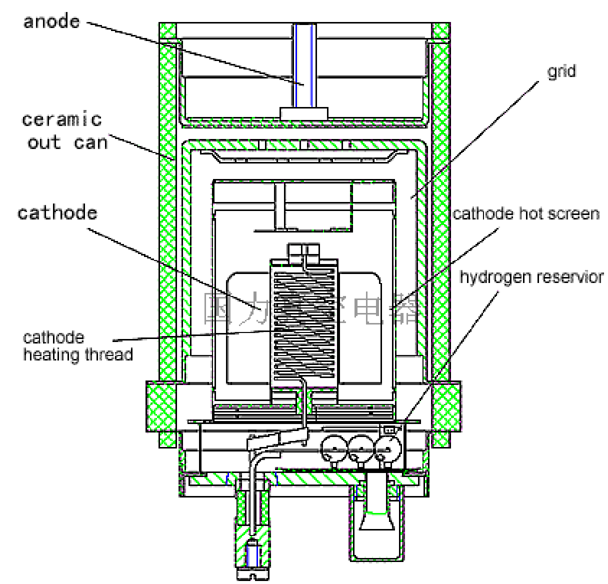
- ❖ Used to switch high voltage on and off very quickly
- ❖ Important components of the pulse modulator, pulse forming network (PFN)
  - That generates short pulses to both gun and klystron or magnetron
- ❖ Typical pulse is 50 kV with 4 μs duration
- ❖ Field with gas (hydrogen) for high speed switching, low pressure ~0.5 torr

Thyratron



- No current between cathode and anode in OFF state
- By applying positive voltage to the control grid, plasma created at the grid and quickly drifts to the provide conduction path from cathode to anode, ON state
- “Hot thyratron” as a heater to make ionization much easier and the Grid more sensitive
- Once turned on, it remains conducting as long as there is current flowing
- When anode voltage or the current falls to zero, it switches off

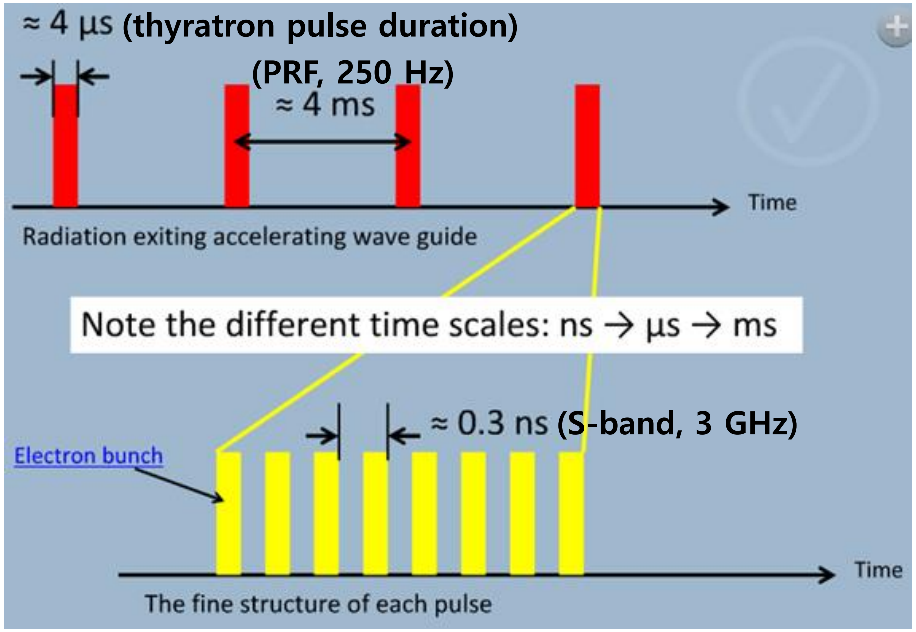




Structure of Hydrogen Thyratron

Linac Pulse

- ❖ Pulses from thyratron ~ 4 μs, sent simultaneously to both gun and klystron (or magnetron)
  - give current to gun and power to wave guide → radiation
- ❖ Electron bunch up inside the wave guide: resonant freq. (3 GHz for S-band → 0.3 ns)
- ❖ Train of bunches of electrons is generated as long as the pulse from the thyratron is on (radiation pulse ~ 4 μs)
- ❖ Pulse repetition frequency (PRF) ~ 250 Hz
  → interval between consecutive pulses ~ 4 ms long
  → duty cycle ~ 0.1%



- ❖ For 300 mu/min
  - beam current for photon ~ 100 mA (peak current during one pulse)
  - beam current for electron ~ 1 mA

  ← low efficiency of e to X conversion
  ← beam attenuation in the target and filter

C. Linac x-ray beam

- ❖ Bremsstrahlung x-rays

- ❖ Target is water cooled and thick enough to absorb most of the incident electrons

- ❖ Electron energy is converted into a spectrum of x-ray energy
  E_{max} (MV) = $E_{ins.\ Elec}$ (MeV)

- ❖ Average photon energy, E_{ave} ~ 1/3 of E_{max}

- ❖ Electron beam → MeV
  - because it is almost monoenergetic beam

- ❖ Photon beam → MV
  - because heterogeneous in energy, as if tube voltage

D. Electron beam

- Narrow pencil beam about 3 mm in diameter

- Strike an electron scattering foil (usually lead) to spread the beam,

- Uniform electron fluence across the treatment field

- Thickness → most electrons are scattered instead of suffering bremsstrahlung

- Small fraction is still converted into bremsstrahlung → x-ray contamination of the electron beam

- Photon contamination: scattering foil, collimator walls or other high-Z materials in beam pass

E. Treatment head

- Thick shell of high density shielding material such as lead, tungsten, or lead-tungsten alloy

- Shielding against leakage radiation in accordance with radiation protection guidelines

F. Target and flattening filter

- Flattening filter to make intensity uniform across the field

- Usually lead, although tungsten, uranium, steel, aluminum, or a combination of them

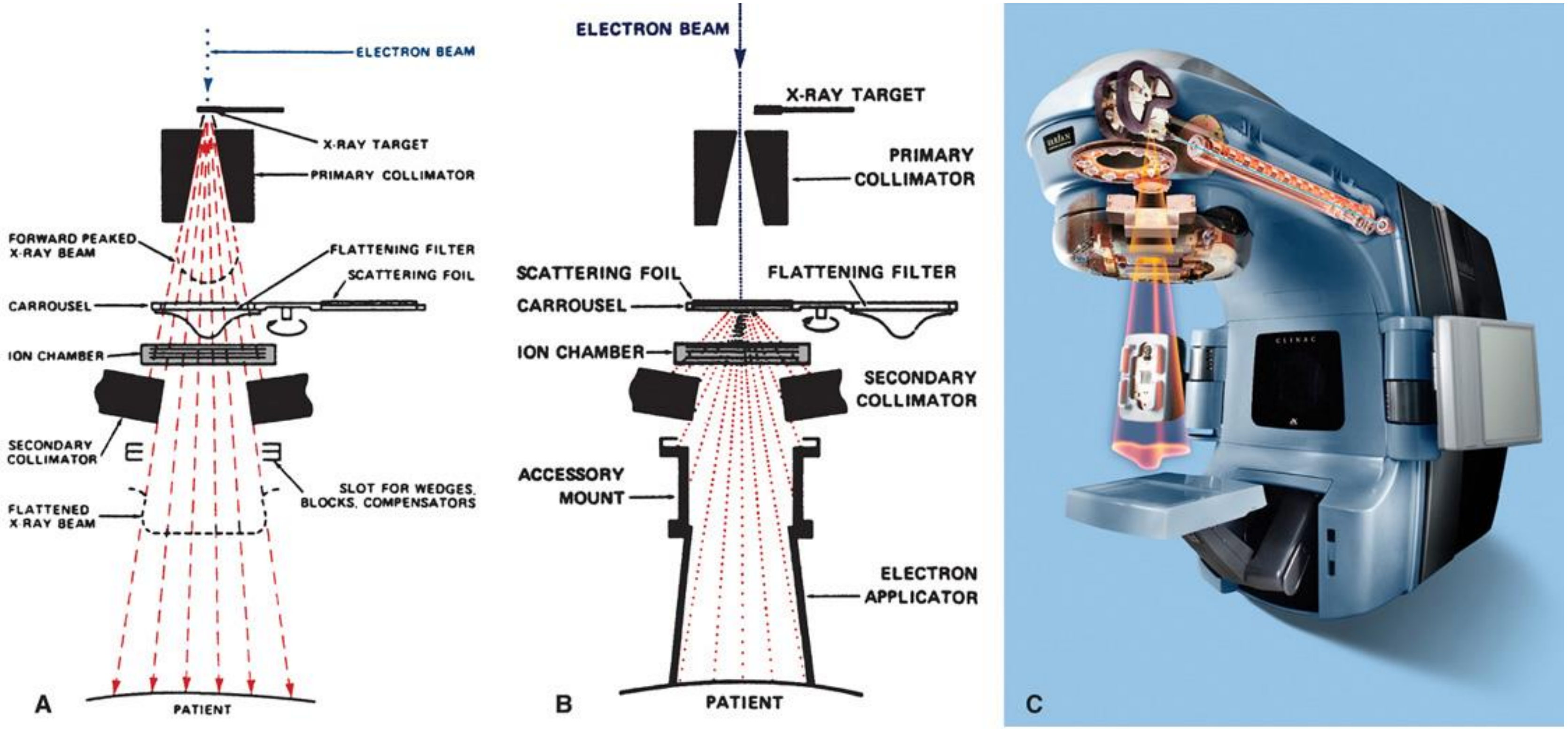


Figure 4.8. Components of treatment head. **A:** X-ray therapy mode. **B:** Electron therapy mode. (From Karzmark CJ, Morton RJ. *A Primer on Theory and Operation of Linear Accelerators in Radiation Therapy*. Rockville, MD: U.S. Department of Health and Human Services, Bureau of Radiological Health; 1981, with permission.). **C:** A cut-away diagram of the linac (from Vaian Medical Systems: www.varian.com, with permission.)

G. Beam collimation and monitoring

❖ Fixed primary collimator

❖ flattening filter (or scattering foil)

❖ dose monitoring chambers

- several ion chambers or a single chamber with multiple plates
- Usually transmission type (flat parallel plate chambers), but cylindrical thimble chambers in some linac
- Monitor dose rate, integrated dose, field symmetry
- Ion collection efficiency must remains unchanged with dose rate change
- Bias voltage 300 ~ 1000 V
- Usually sealed chamber not to influenced by temp. and air pressure of outside air
- Should be periodically checked for leaks

- X-ray collimator system
  - movable jaws (lead or tungsten blocks)
  - Move so that the block edge is always along a radial line passing through the target
- Field size definition is provided by a light localizing system
- Electron collimation system
  - electrons scatter readily in air → must be achieved close to the skin surface of the patient
  - scattering of electrons from the collimator surfaces and movable jaws
  - Dose rate can change by factor of 2 or 3 as jaws are fully opened
  - Output critically depends on the surface area of the collimator
    → wide open jaws + auxiliary collimator (as trimmers, sometimes cones) down to the skin surface

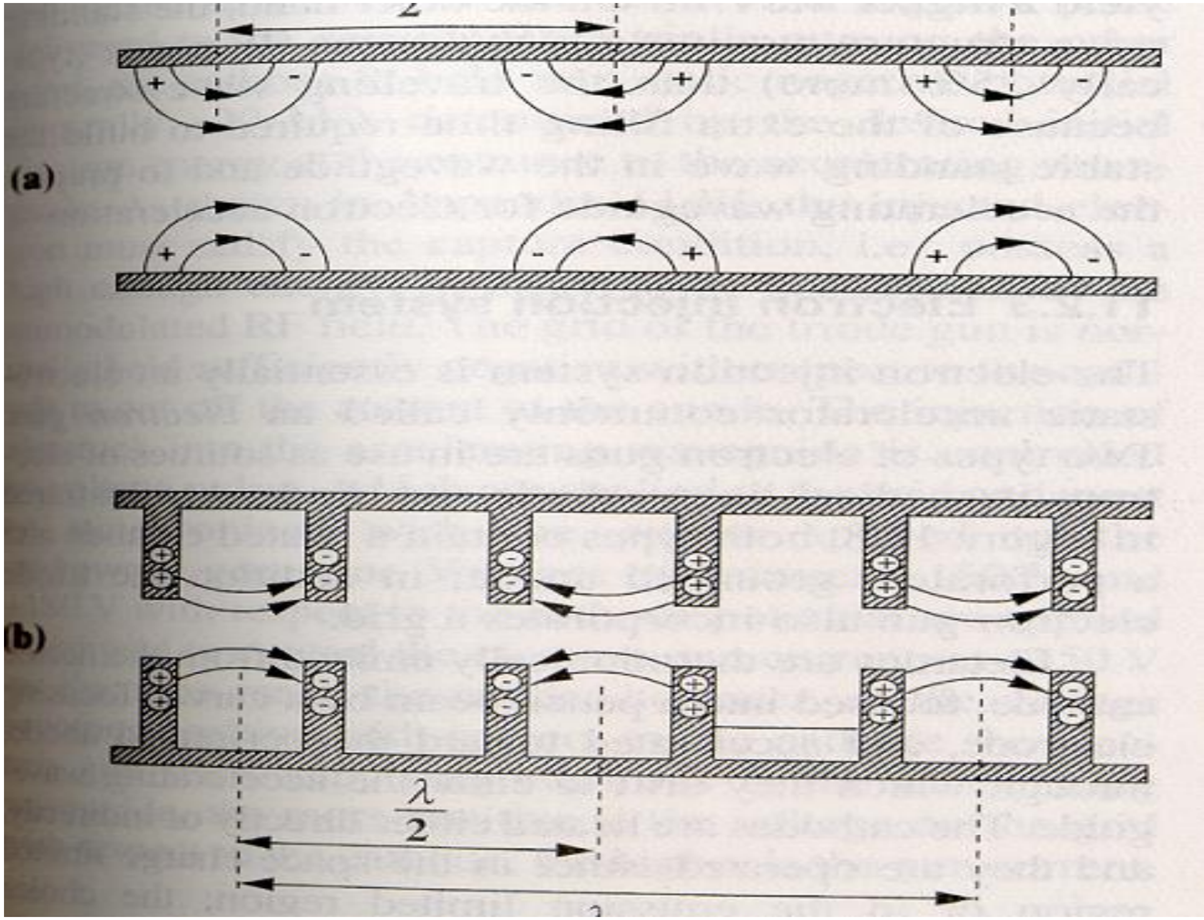
H. Gantry

- Isocenter: the point of intersection of the collimator axis and the axis of gantry rotation
- Isocentric treatment

Properties of waveguide

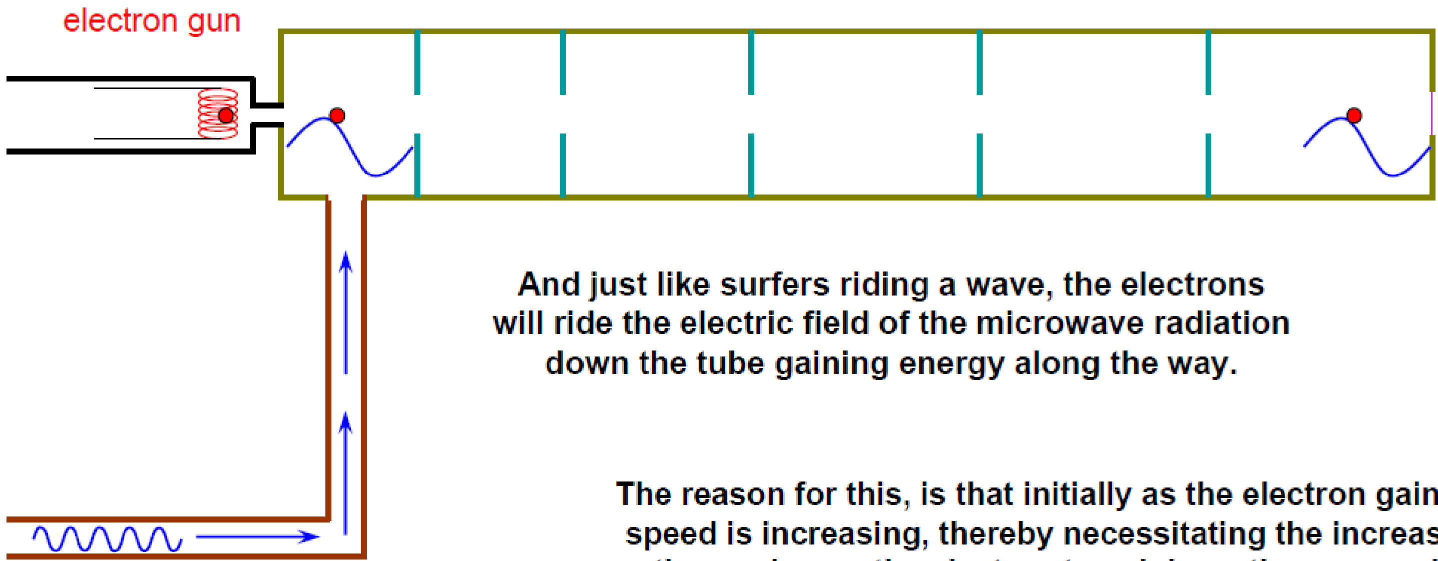
- Evacuated/gas filled metallic structure used in transmission of microwaves.
- Propagation-Maxwell's eqs & boundary condition at the wall : Et=0, Hn=0
- **Uniform waveguide:** simple cylindrical metal tube-can not be used for electron acceleration in a linac. (v_{ph}>C)
- **Loaded wave guide**: uniform wave guide+periodic perturbation to make v_{ph}<C & enable the electron to follow the electric field pattern.
  - Exist a series of cavities: s-band (2856 MHz) cavity size=10cm diameter, 2.5-5cm in length.
  - purpose of cavities:* to couple & distribute micro-power * to provide a suitable E pattern with Vph<C

Traveling electric field pattern & charge distribution (a) for a uniform waveguide (b)disk-loaded waveguide



Traveling wave structure

1) Traveling wave: microwave enter @ gun side. Propagate to the high E end- absorbed without any reflection OR exit the waveguide



And just like surfers riding a wave, the electrons will ride the electric field of the microwave radiation down the tube gaining energy along the way.

The reason for this, is that initially as the electron gains energy there speed is increasing, thereby necessitating the increased spacing of the washer as the electron travel down the wave guide. This will allow for the electrons and the microwave radiation to stay in step. But as the electrons gain energy, they very quietly approach the speed of light. Then spacing of the washers becomes uniform, because at this point an increase in energy by the electrons is NOT manifested as an increase in speed BUT as an increase in mass.

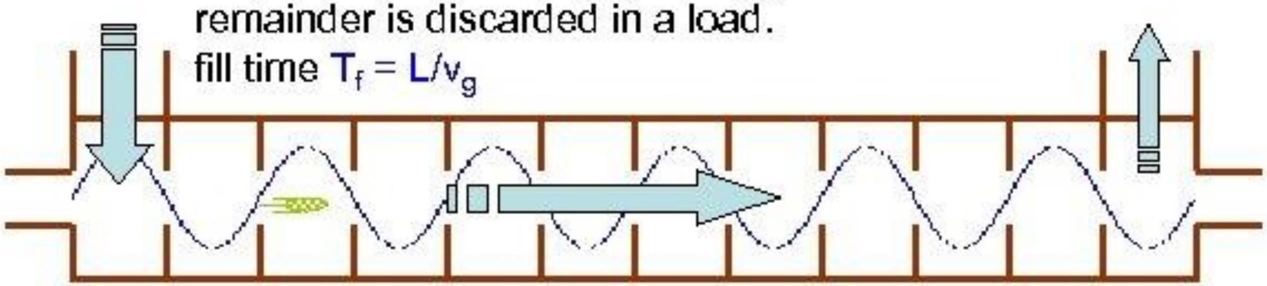
Traveling Wave Structure

input and output waveguides

RF pulse travels through, losing power to walls and beam

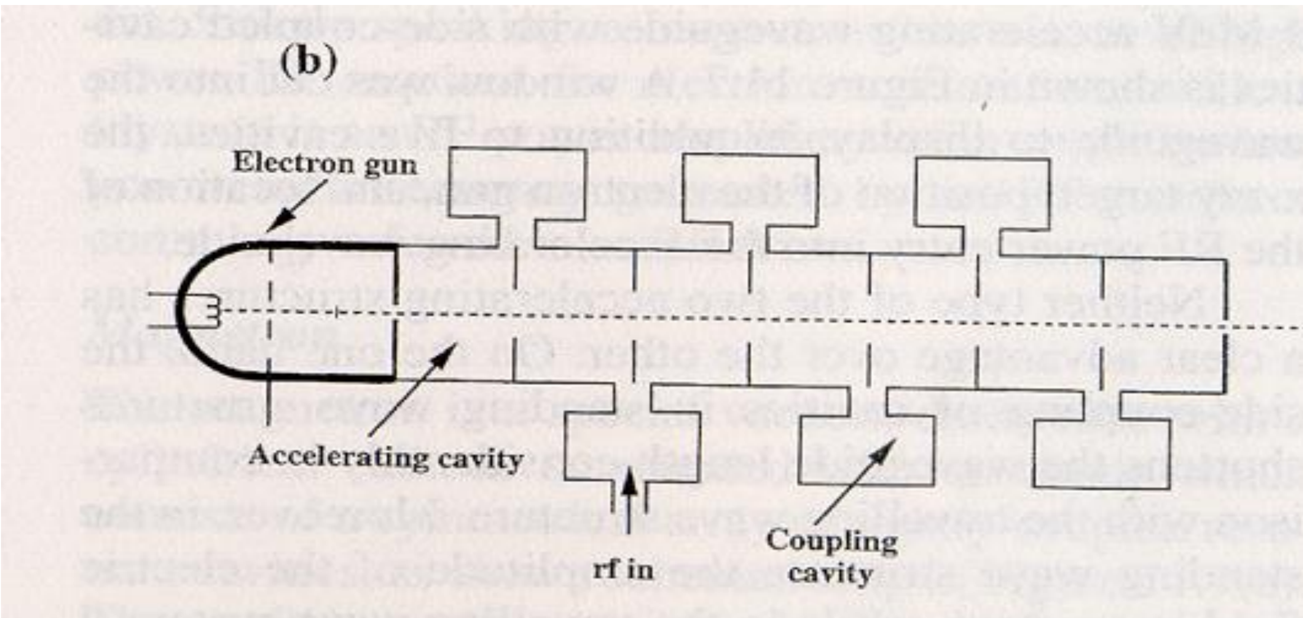
remainder is discarded in a load.

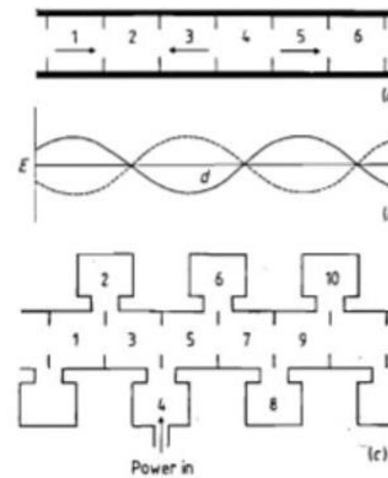
fill time $T_f = L/v_g$



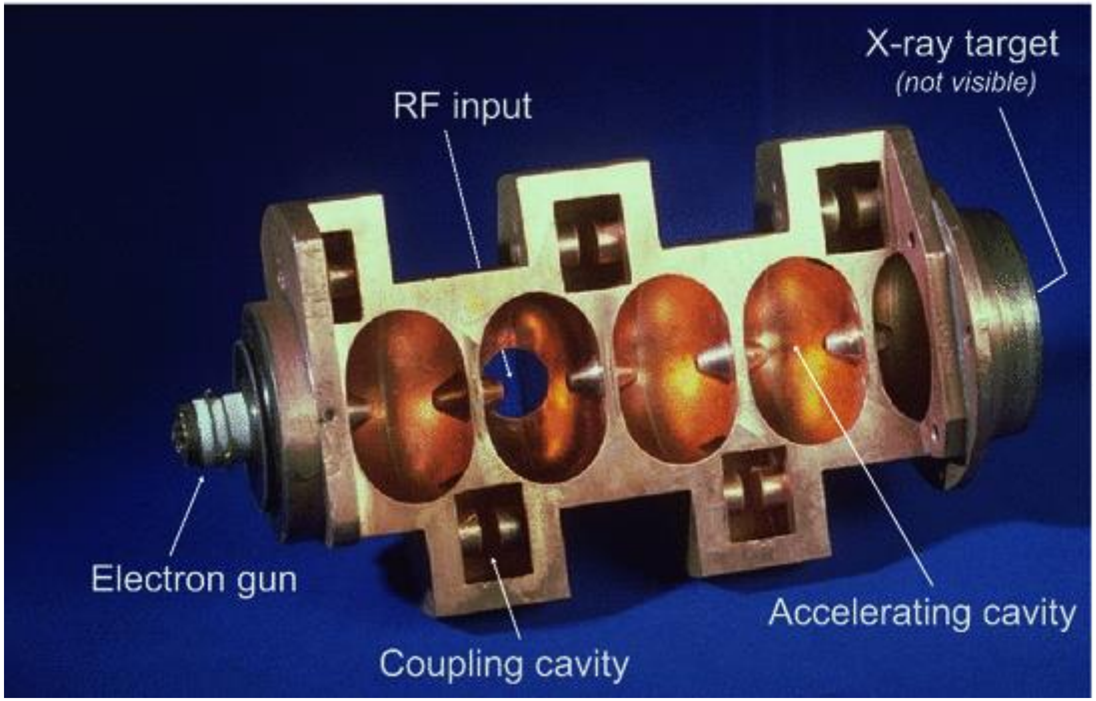
2)Standing wave

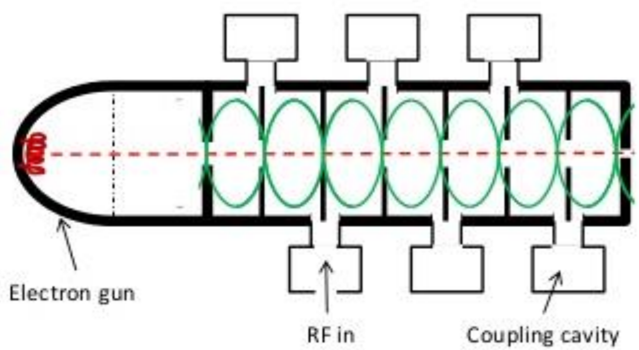
❖ Both ends is terminated with a conducting disk to reflect the micropower with $\pi/2$ phase change.->build up standing wave.





No electric field in the coupling cavity only for coupling→ effectively shortening the length of the waveguide.





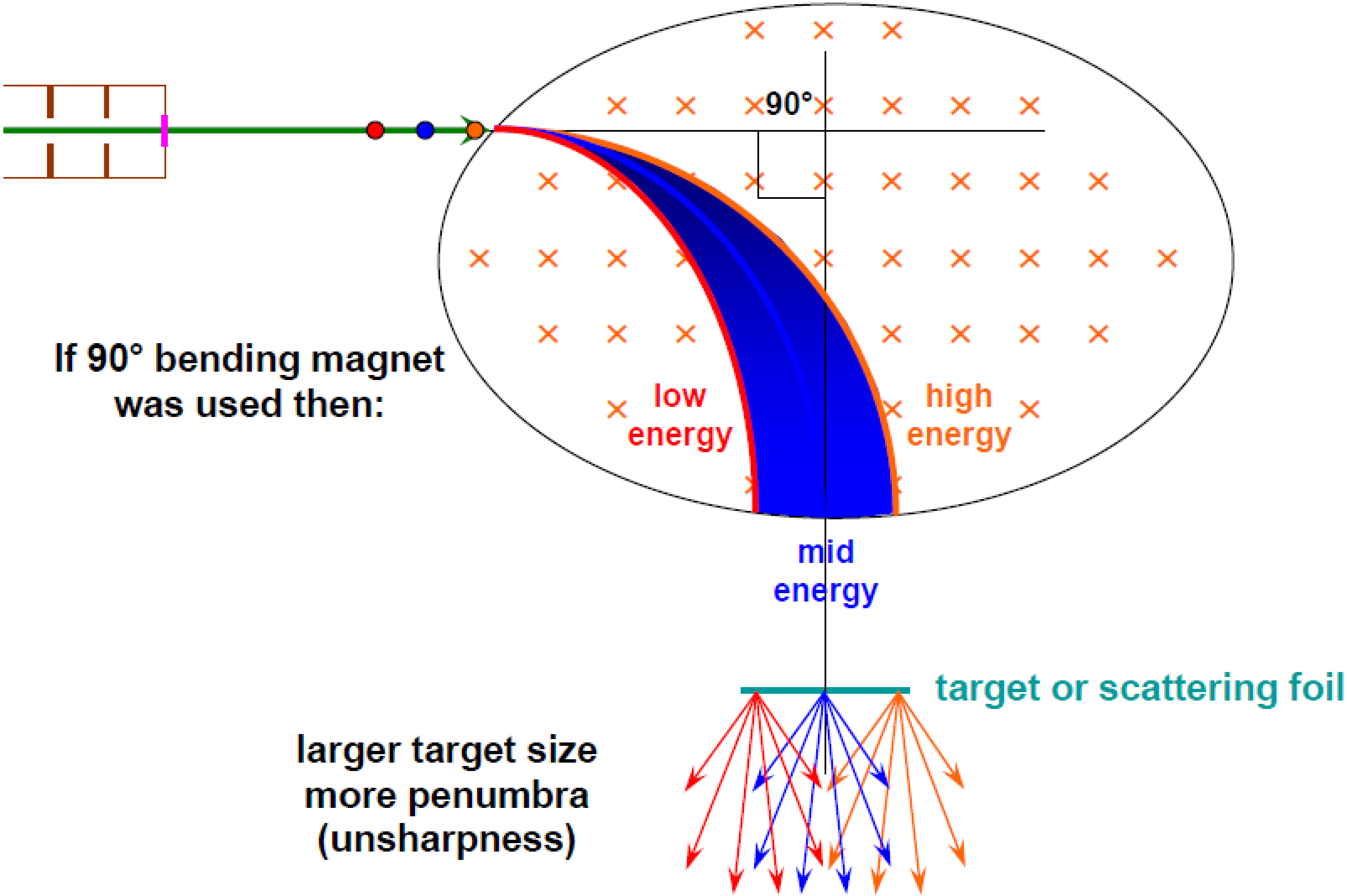
Standing wave structure

- RF power can be supplied at any convenient point.
- Side coupling cavity can shorten the waveguide length
- E field in the guide is constant in the standing wg, but E field is attenuated in a traveling wg.
- For a given microwave peak power level (typical 2.5 MW)
- standing wave structure > higher electron energy / length

  20 MeV/m 5MeV/m
- Need more mean RF power (25%) in standing WG.

Bending magnet

If 90° bending magnet was used then:



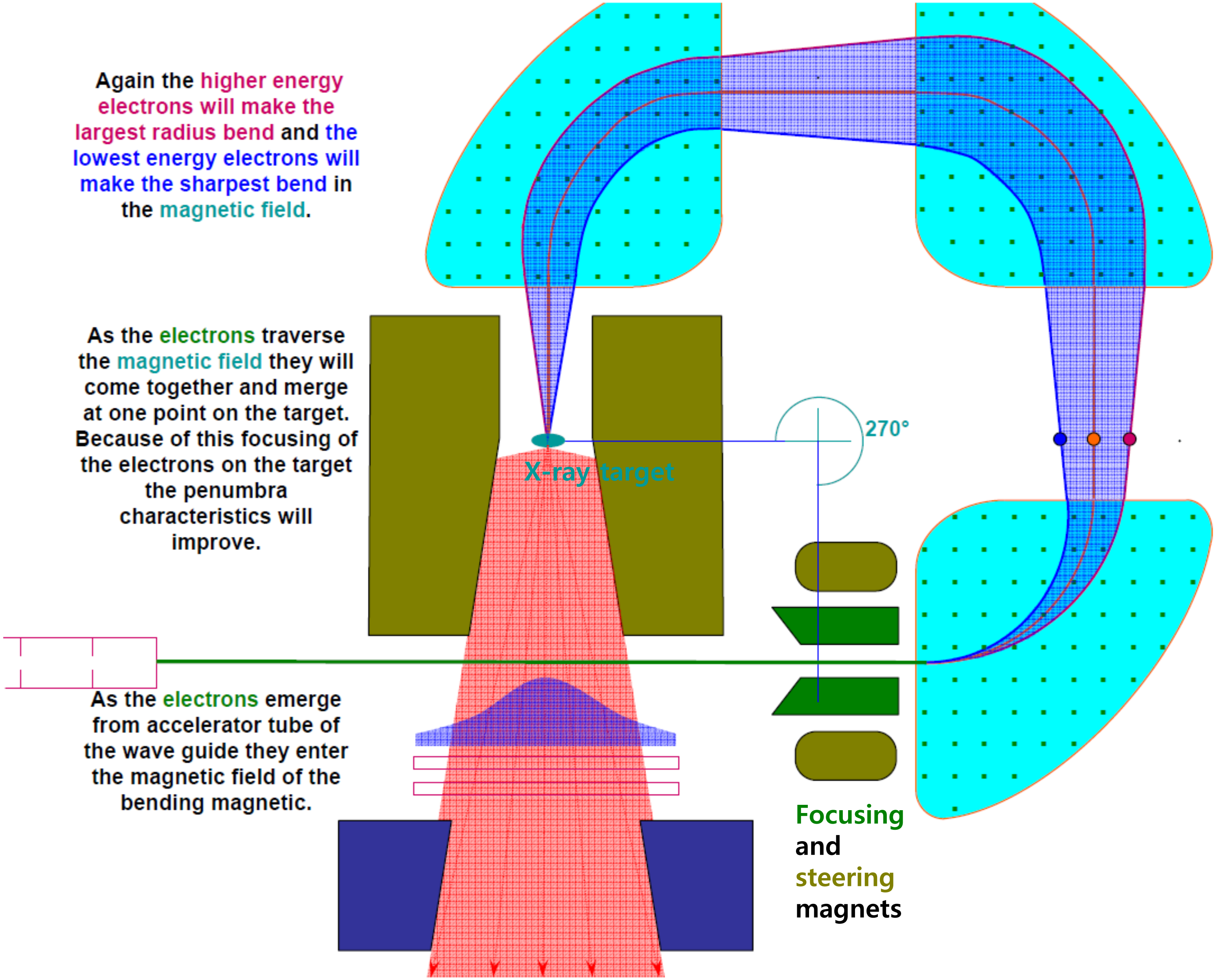
larger target size
more penumbra
(unsharpness)

Bending magnet

Again the higher energy electrons will make the largest radius bend and the lowest energy electrons will make the sharpest bend in the magnetic field.

As the electrons traverse the magnetic field they will come together and merge at one point on the target. Because of this focusing of the electrons on the target the penumbra characteristics will improve.

As the electrons emerge from accelerator tube of the wave guide they enter the magnetic field of the bending magnetic.



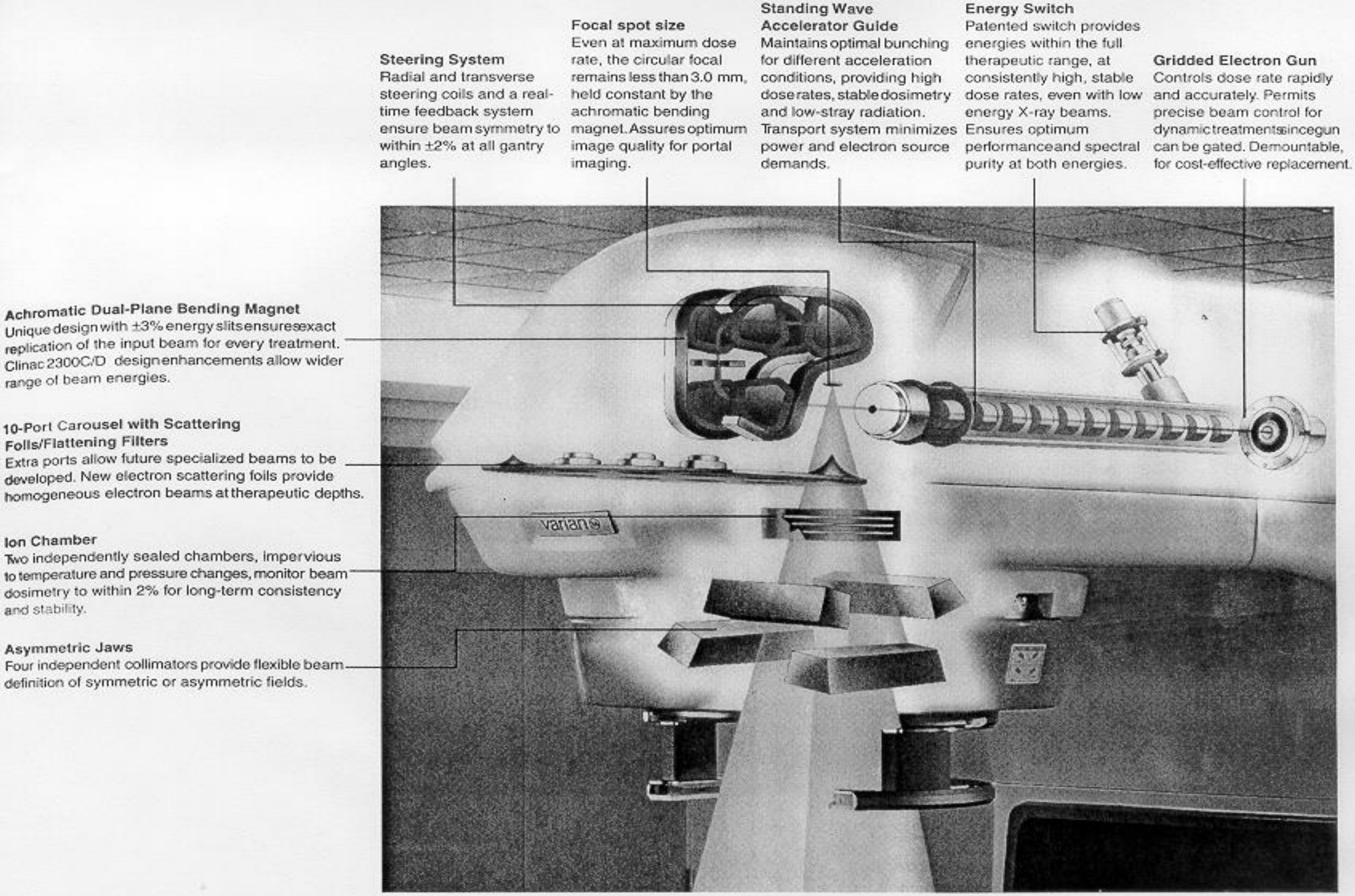
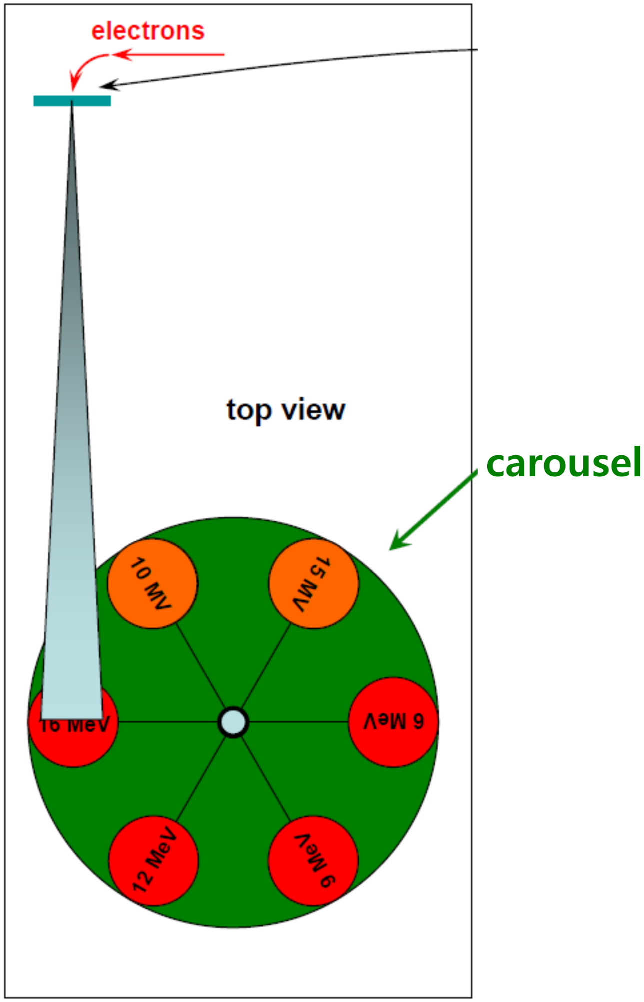
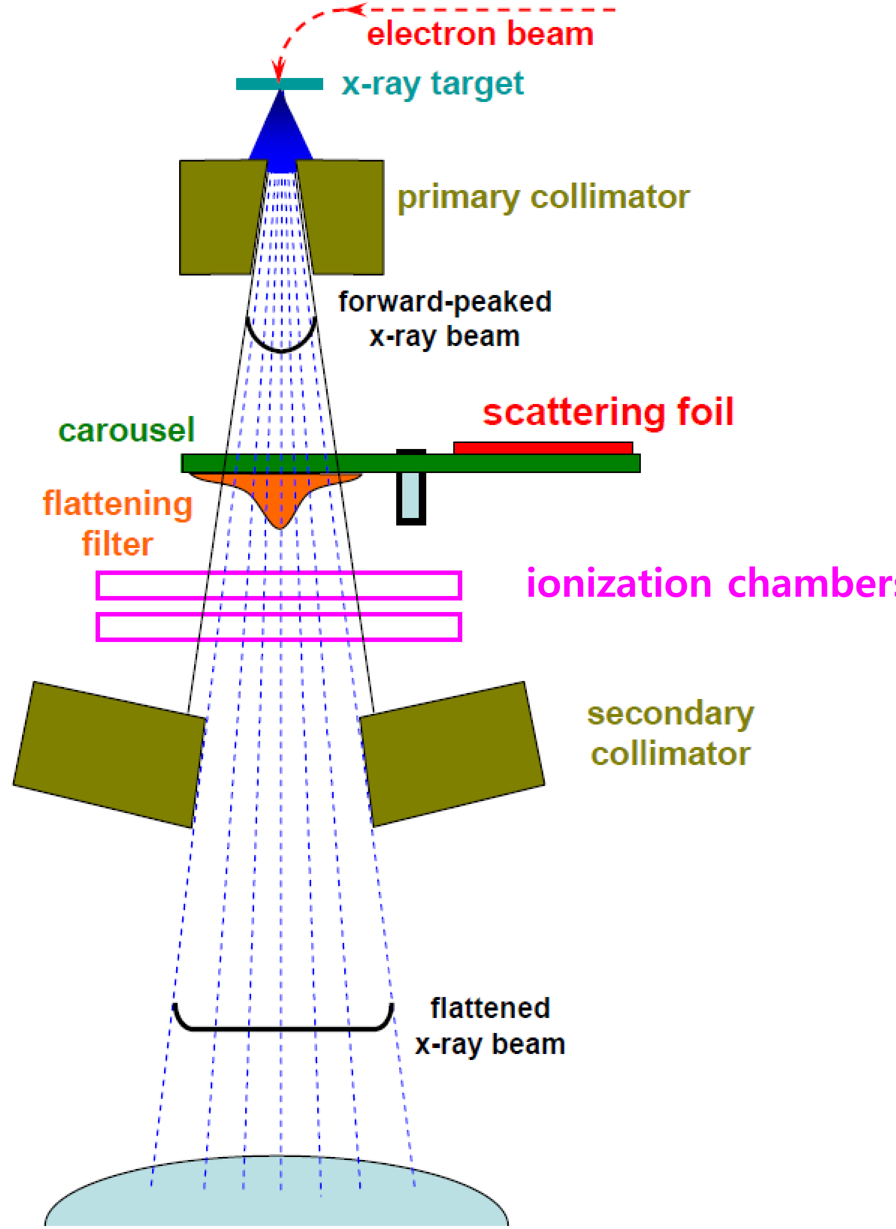


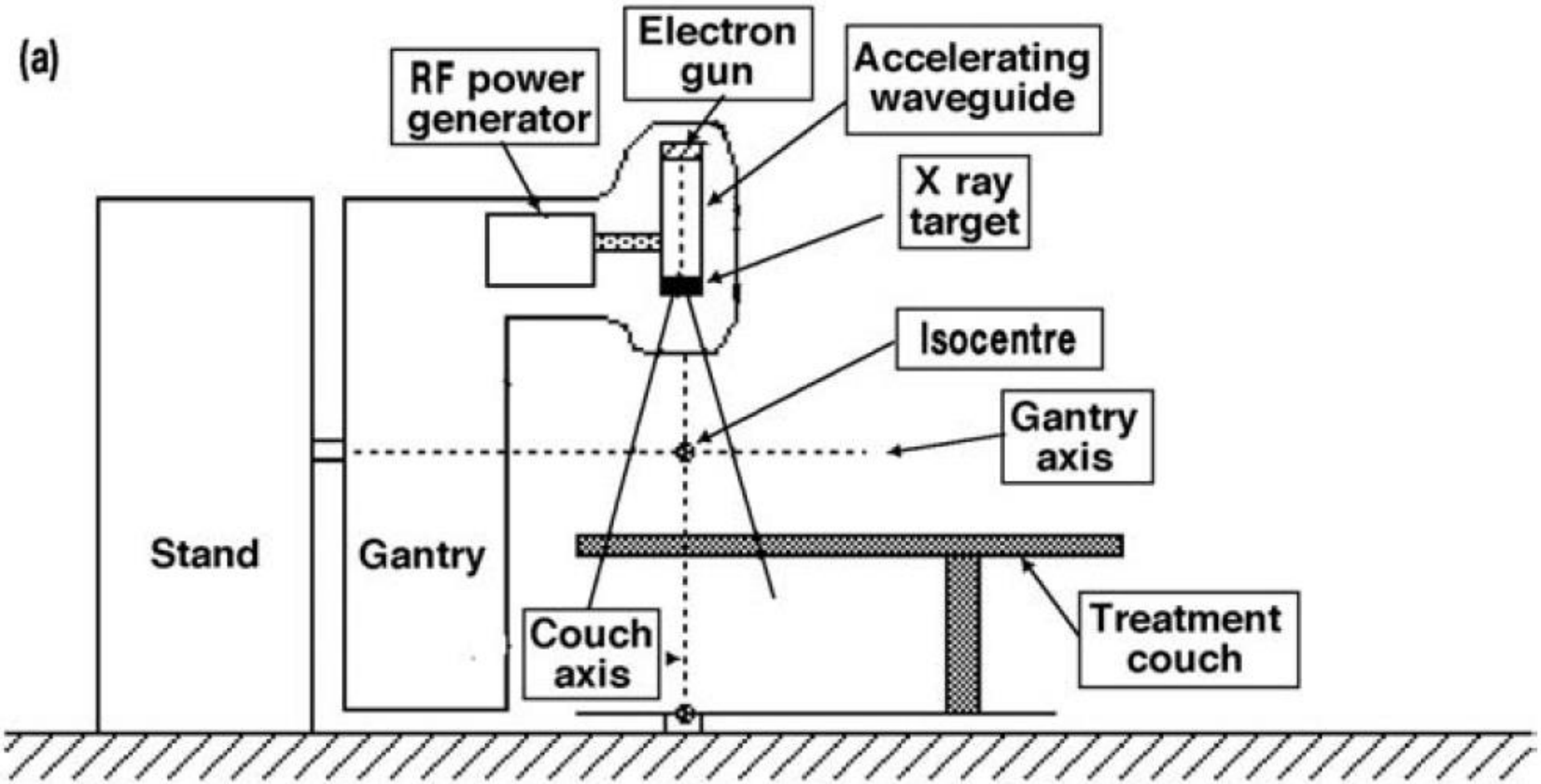
Figure 7-14. The major components of the gantry include the electron gun, accelerator guide, and treatment head, which includes components such as the bending magnet, beam-flattening filter, ion chamber, and upper-lower collimator jaws. *(Courtesy Varian Medical Systems.)*


electrons
top view
carousel
10 MV
15 MV
6 MeV
12 MeV
9 MeV


electron beam
x-ray target
primary collimator
forward-peaked
x-ray beam
carousel
scattering foil
flattening
filter
ionization chambers
secondary
collimator
flattened
x-ray beam

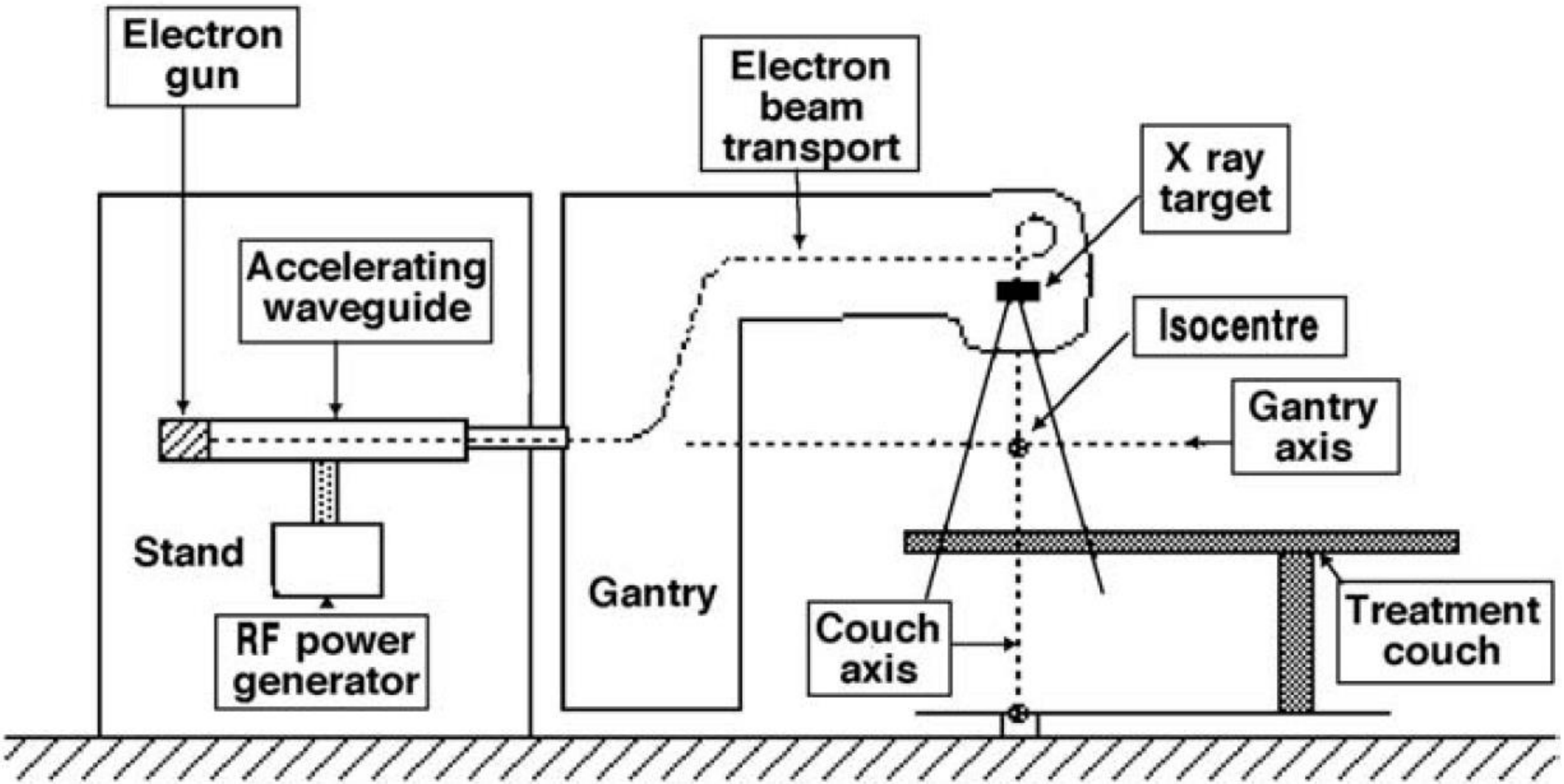
Accelerating wave guide

Length: ~30cm for 4MeV, ~150cm at 25 MeV



4-6MeV: No wave beam transport, no electron therapy option.

Wave guide for electron energy 8-15 MeV(intermediate energy), 15-30 MeV (high energy)



Energy is determined by amount of **RF power** and **number of electrons** injected. This ratio must be correct in order to pass through bend magnet energy slits.

Bend Magnet Shunt current and fixed +/- 3% Energy Slits pass only electrons of proper energy. The electrons outside this window strike the energy slits and are converted to heat.

VARIAN medical systems

Trubeam

Trilogy

iX

EDGE

Halcyon

ELEKTA

Versa HD

Infinity

Synergy

Unity

ACCURAY

ACCURAY CyberKnife

TomoTherapy

H

HD

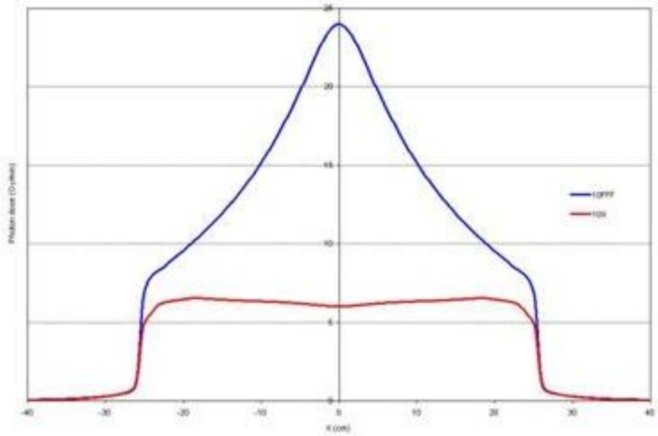
HDA

MRIDIAN (ViewRay)

Theratron (Co-60)

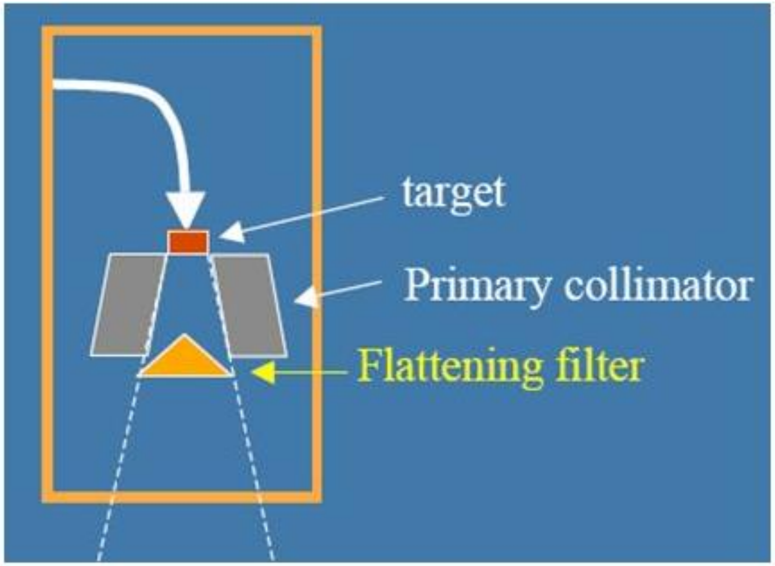
Flattening filter

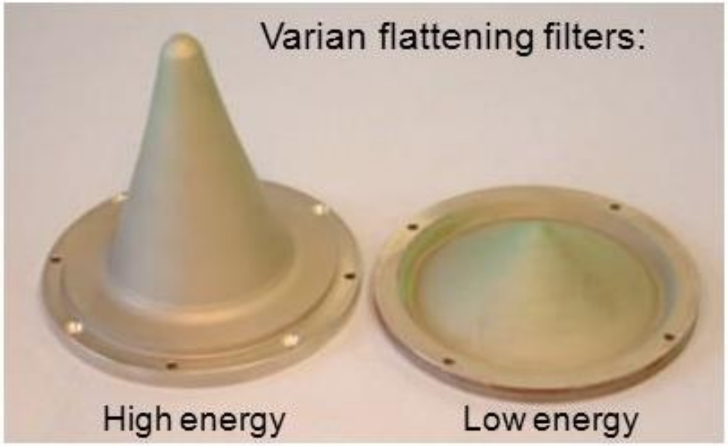
1. Bremsstrahlung is forward-peaked
2. Convenient with flat dose profile



⇒ Use flattening filter:

- Cancellation of off-axis intensity variation
- Reduction in dose rate
- Off-axis photon energy spectrum variation



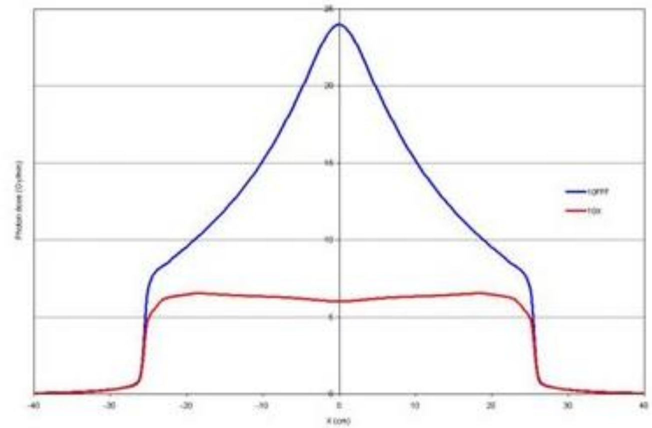


Pb for Low E
Pb or W up to 15 MeV
Fe and Pb core for 20~25 MeV
Al or Fe for higher E

Flattening filter

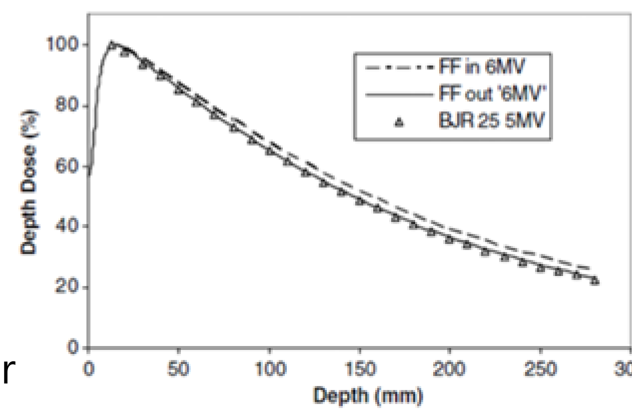
Flattened beams

Make dose calculation for simple algorithms easier
So much head scatter
→ output factor can vary with FS



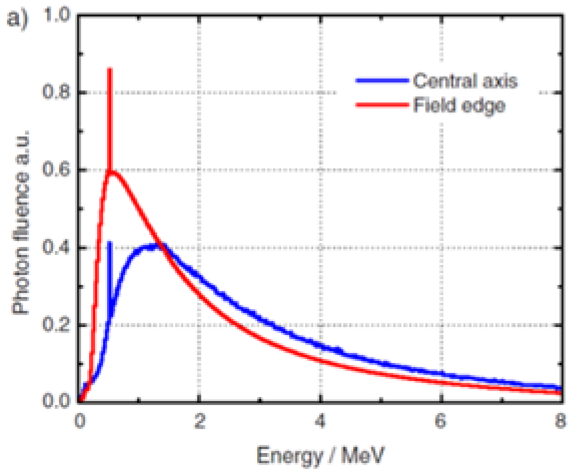
FFF beams

- ❖ Cyber knife, Tomotherapy, …
- ❖ Most useful for small field techniques (SBRT, IMRT, …)
- ❖ A softer energy spectrum
- ❖ Higher photon energy fluence, higher dose per pulse
- ❖ Reduced electron contamination to the beam
- ❖ Reduced head scatter (head leakage 50%)
- ❖ Higher dose rate → decrease treatment time
- ❖ Reduced sensitivity to beam positioning and energy var
- ❖ Potentially increased dose calculation accuracy
  - ← reduced output factor variations
  - ← reduced e-contamination
  - ← reduced leaf transmission

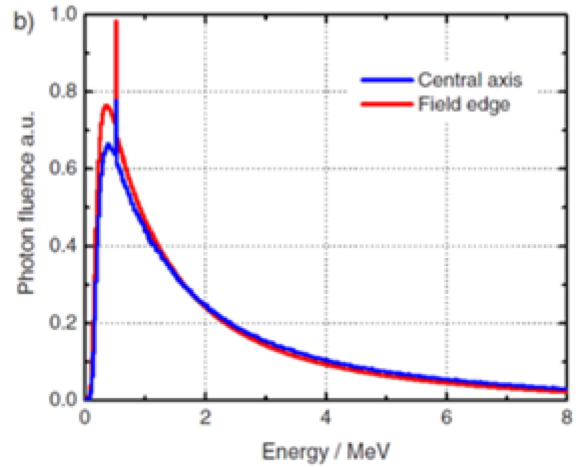


Flattening filter

Flattened beam



FFF beam



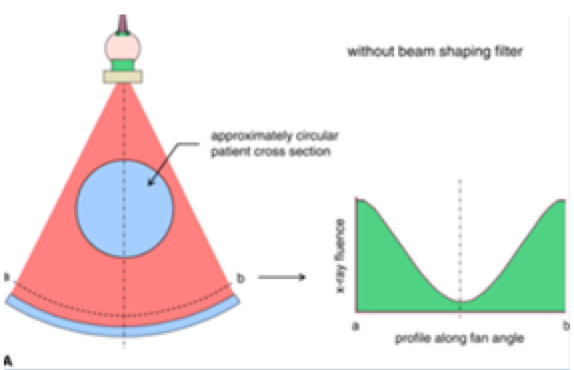
❖ Relative constant energy spectrum across the profile
→ Almost constant profile with depth

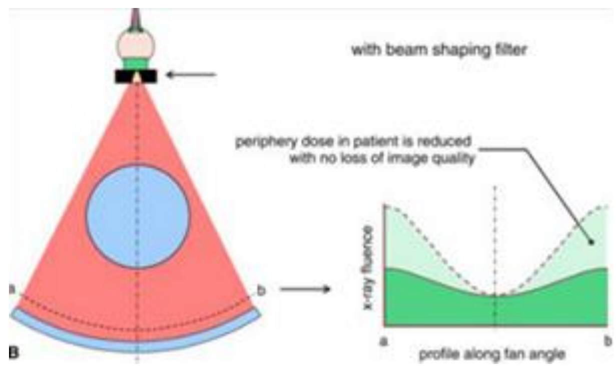
❖ Similar d_{max} across the profile
- Reduced e-contamination → move d_{max} deeper
- Softer spectrum → move d_{max} shallower

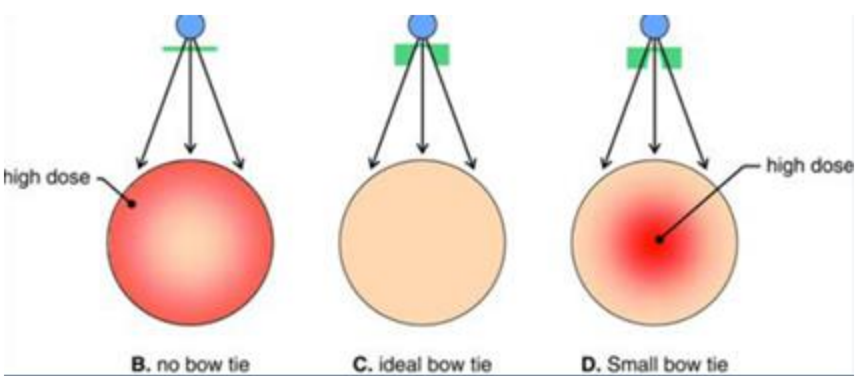
Note)

Bowtie Filter in CT

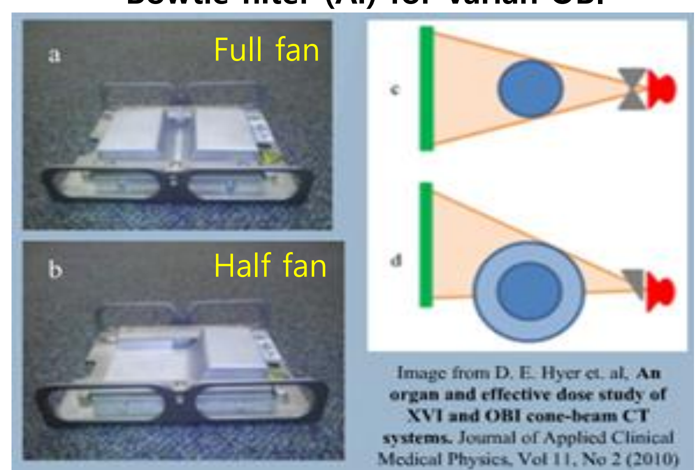
- ❖ Human body anatomy typically has a round cross section
  - thicker in the middle than in the periphery.
- ❖ to reduce the beam intensity at the periphery of the beam
  - corresponding to the thinner areas of a patient's anatomy.
- ❖ Because of their shape they are often referred to as bowtie filters.





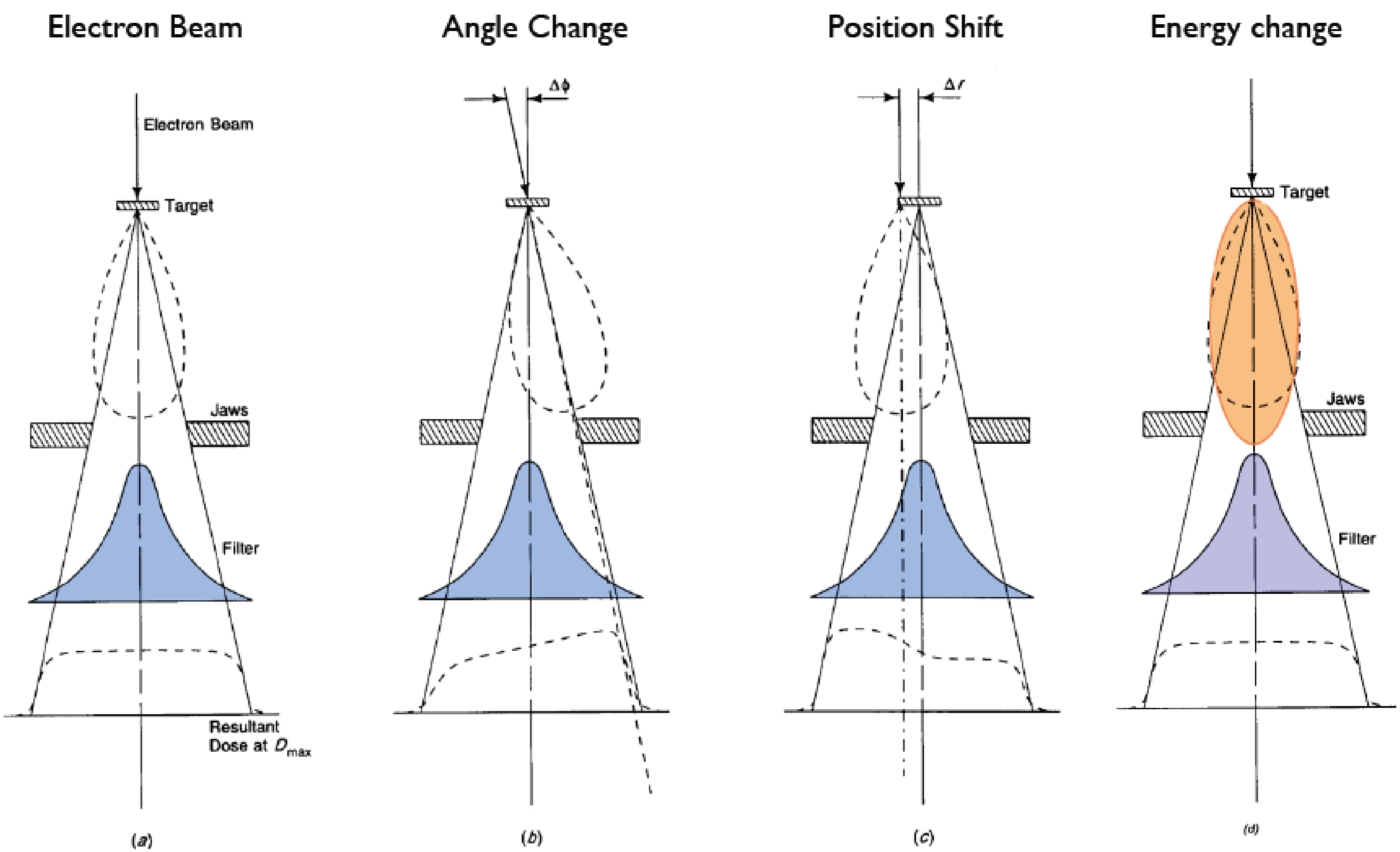


Bowtie filter (Al) for Varian OBI

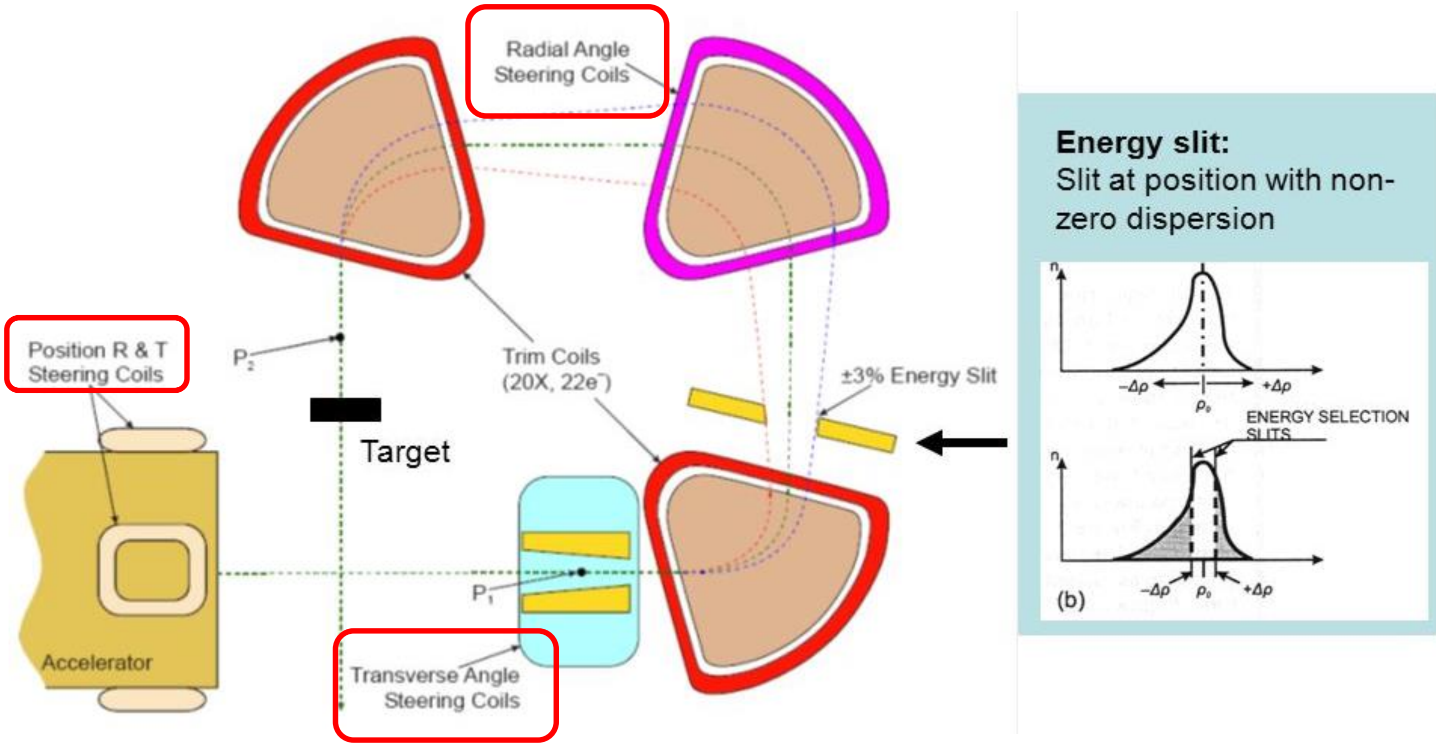


Flatness and Symmetry

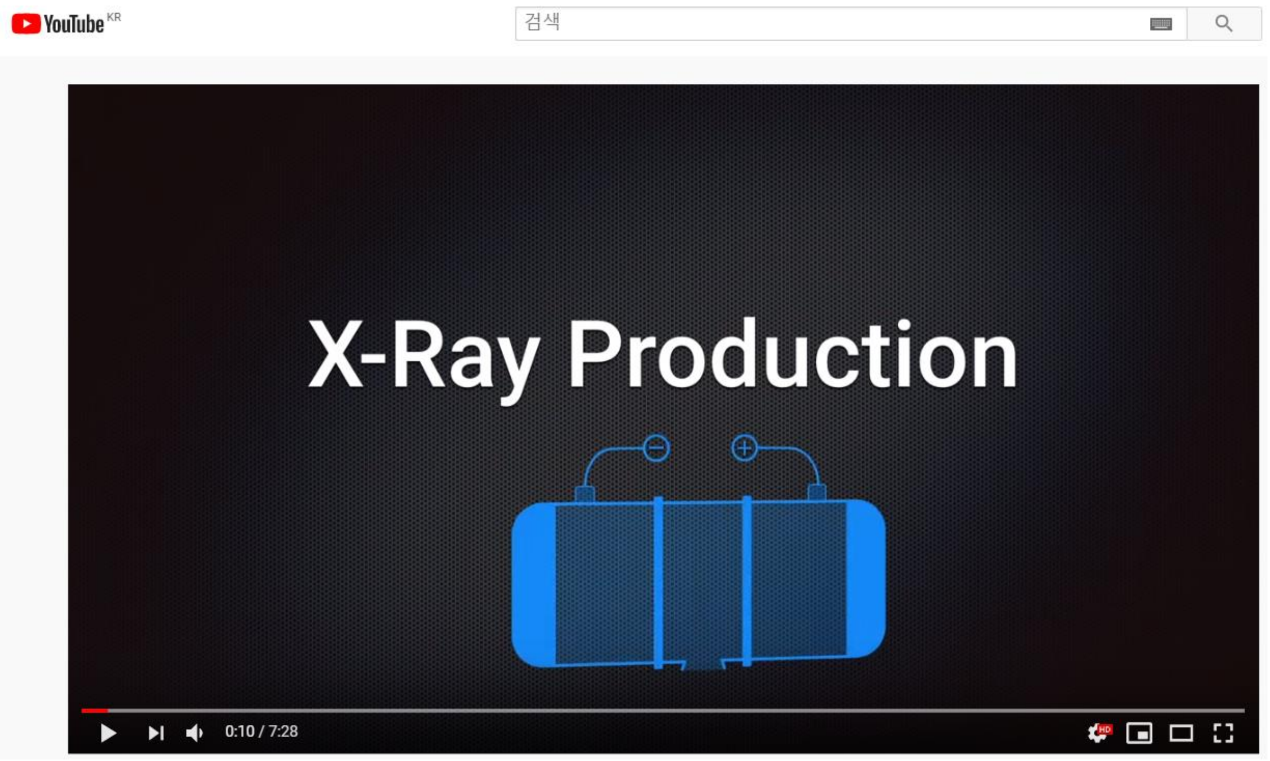
- ❖ Flatness and Symmetry: adjusted by changing position or angle of e-beam to the target
- ❖ Position and angle: by varying the current through the steering coils



Flatness and Symmetry



Radial angle coil primarily adjusts inplane profile
Transverse angle coil primarily adjusts crossplane profile
Buncher coils format and focus e-packets at the beginning of the accelerator guide


YouTube KR
검색
X-Ray Production
0:10 / 7:28