Radiation Generators

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AAPM Review Course – July 19, 2014

Radiation Generators

Topics to be Covered:

A. Kilovoltage x-ray units

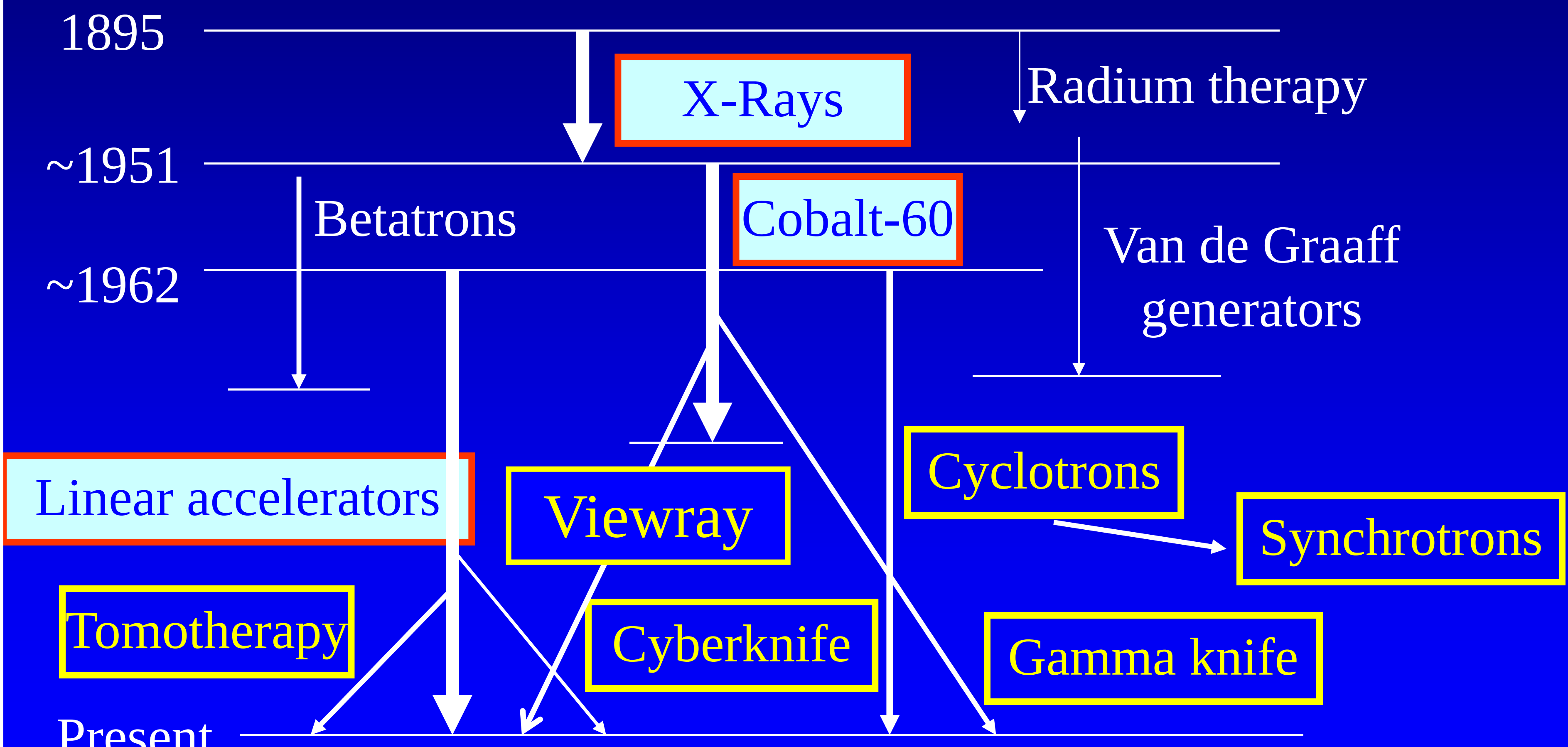
B. Cobalt teletherapy units & Gamma Knife

C. Linear accelerators, Tomotherapy,
Cyberknife & IORT

D. Cyclotron (protons)

E. Properties of megavoltage beams

Evolution of Radiation Generators



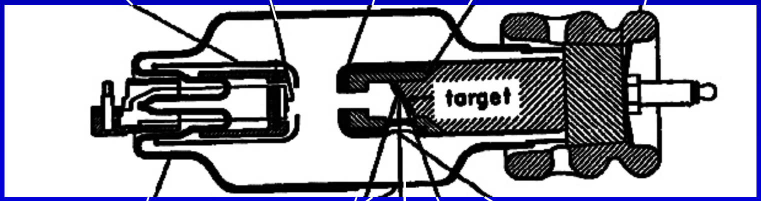
Kilovoltage Therapy Units (Non-Isocentric)

- **Contact therapy (≤ 50 kV):**
  - Often short SSD, high dose rate machines with small applicator sizes
  - HVL < 2mm Al, with sharp dose fall-off for skin irradiation
- **Superficial therapy: (50-150kV):**
  - SSD's typically up to 20 cm
  - HVL up to 8mm Al (150kV)
- **Orthovoltage therapy (150-500kV):**
  - Typical energies are 250 and 300 kV with SSD's up to 50cm
  - HVL up to 4mm Cu

<100 kV still has clinical use

All beam qualities have maximum dose at or close to the surface and use fixed applicator treatment. 250 kVp is the "gold standard" for radiobiology.

Orthovoltage Unit – Mainstay of Early Radiation Therapy



1. Stationary, scatter target (W in Cu block)
2. HVL ~ mm Cu
3. Dose rate (current machines):
   - ~260 R/min; HVL = 1 mm Cu
   - ~180 R/min; HVL = 2 mm Cu
   - 50 cm SSD
4. Target angle is ~26°-32° for large field size (20x20)
5. Tube is oil cooled

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Orthovoltage Applicators –SSD R_x

BJR specifies PDDs for both diaphragm limited fields and closed applicators

Cobalt-60 Teletherapy Units

- Source drawer contained in thick, steel encased lead housing to reduce leakage to <0.02 mSv/hr at 1m
- Safety systems ensure that the unit fails in the "OFF" position
- Depth of maximum dose is 0.5 cm for a 10x10 cm^2 field; this drops rapidly with increasing field size due to electron contamination
- ^{60}Co is still the standard beam quality for calibrating ionization chambers ($N_{D,W}$ & N_x)
- These units now come under homeland security regulations

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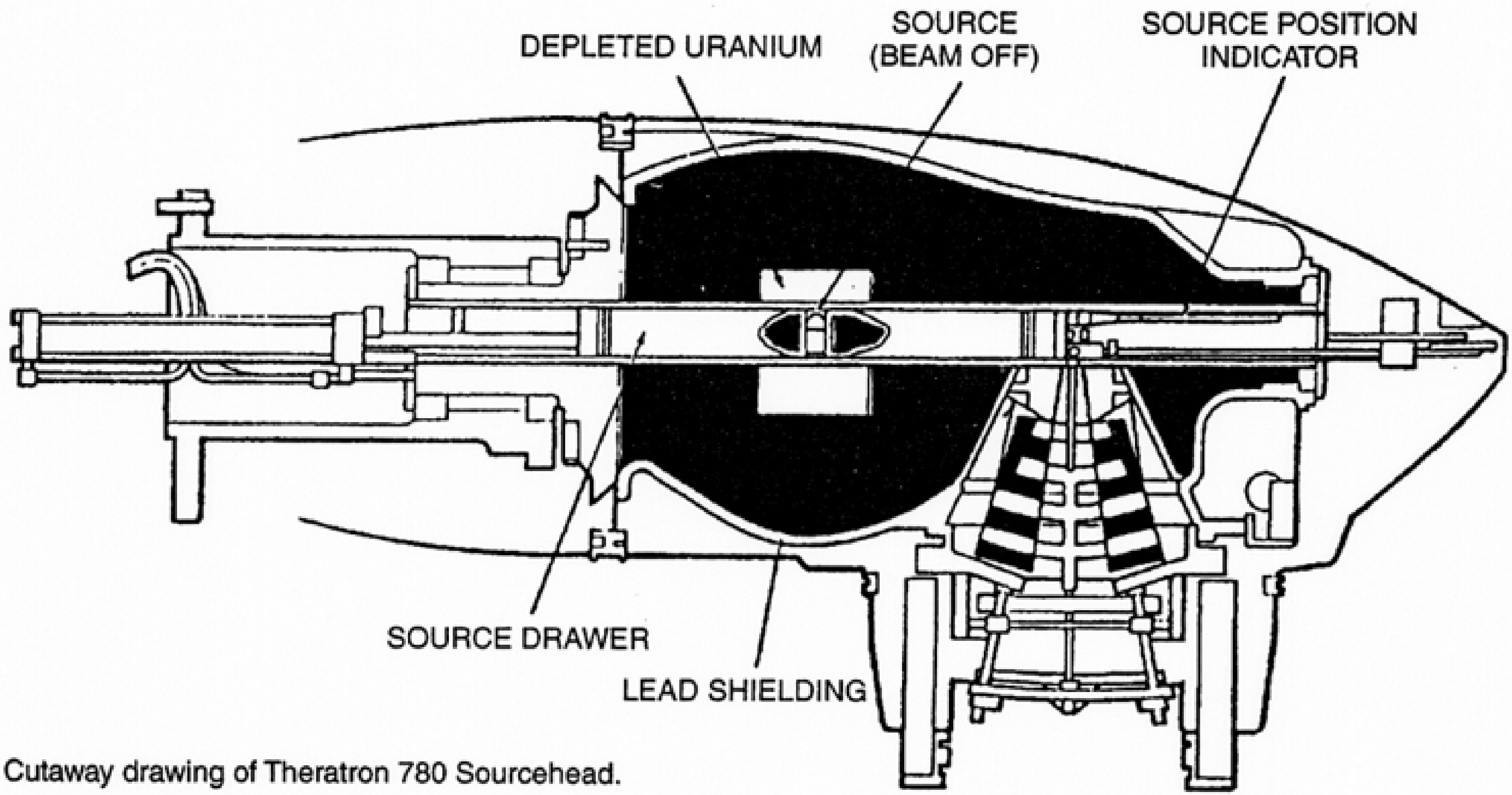
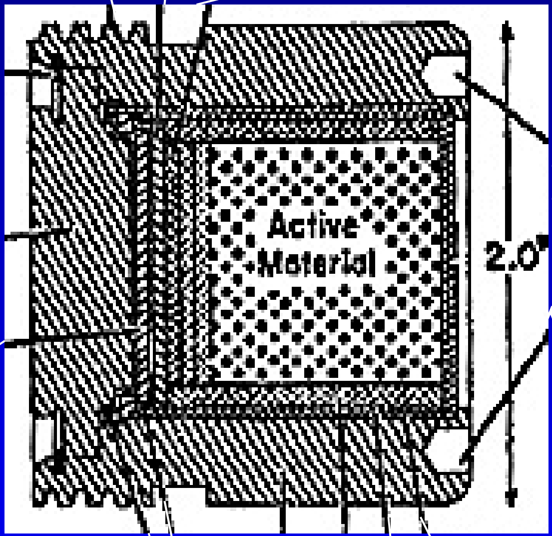
Theratron 780 - Cutaway View



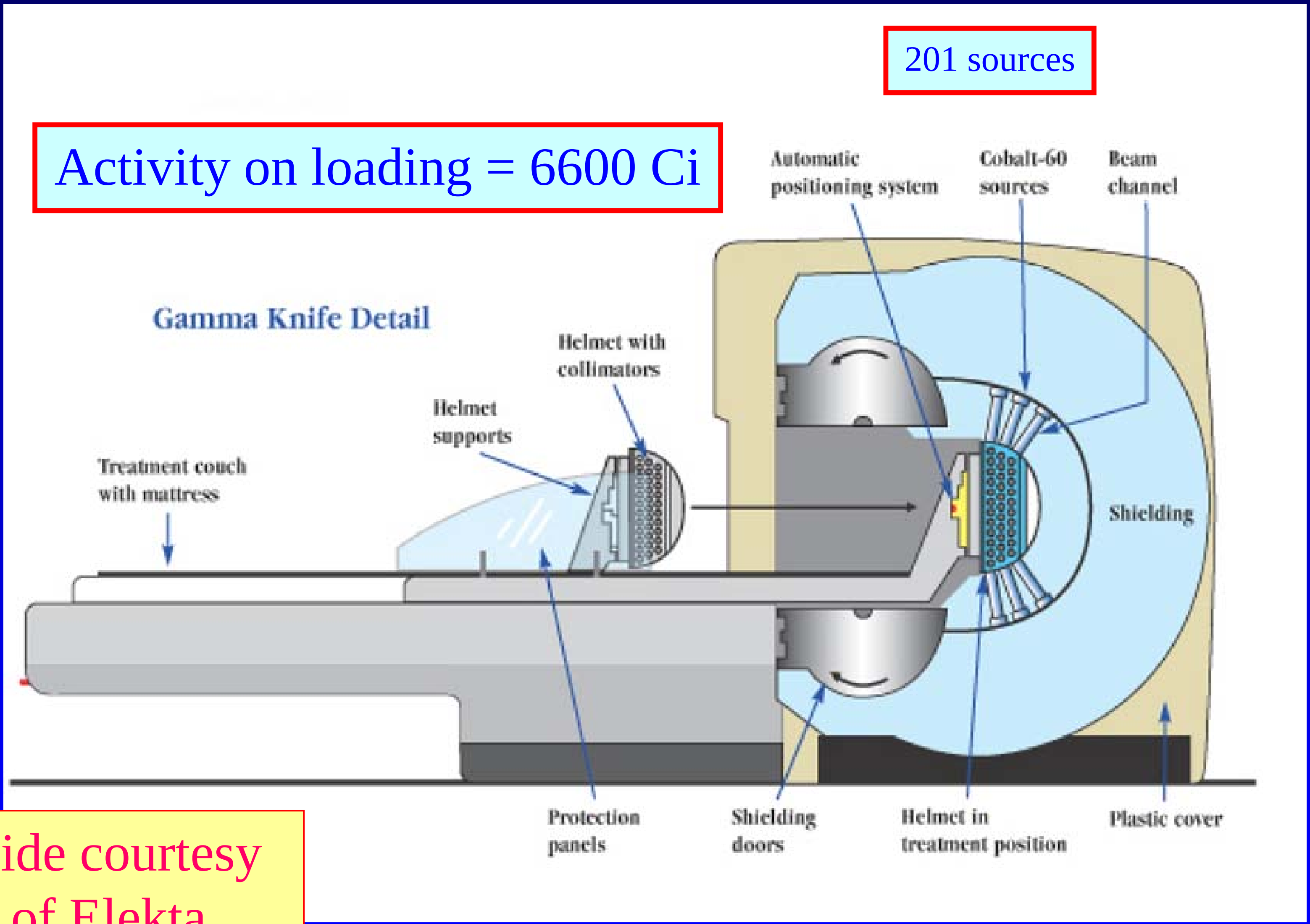
Cutaway drawing of Theratron 780 Sourcehead.

Cobalt 60 Source Construction



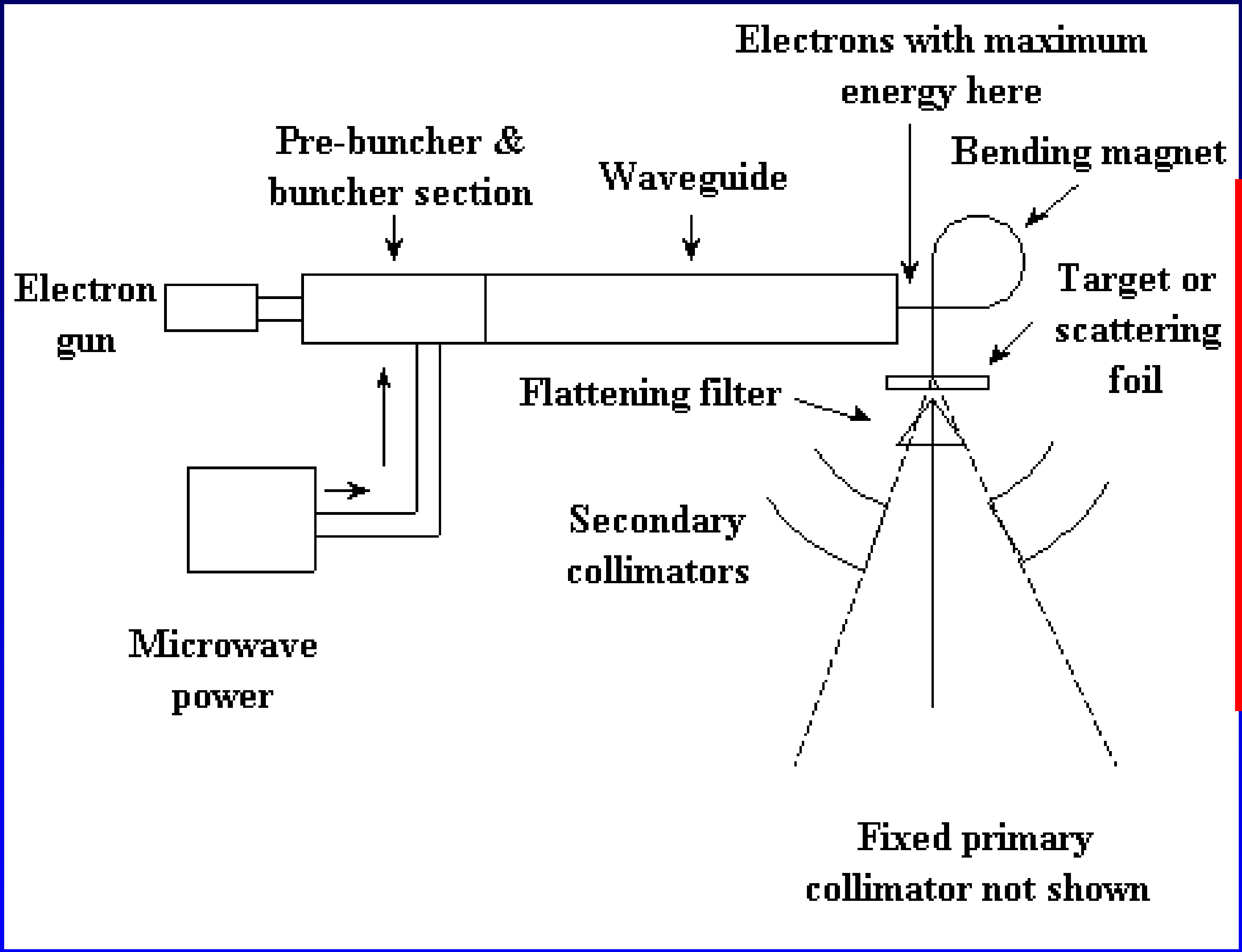
1. source comes with a min. diameter of 1.5cm and can either be in the form of pellets or a solid slug. Thus, the penumbra is much worse than for linacs.
2. clinical sources are typically 10^4 Ci, giving ~240 rad/min at isocentre (80 cm)
3. doubly encapsulated source

Cutaway of Gamma Knife



Slide courtesy of Elekta

Overview of Linac Components



- Gun
- Waveguide
- Power supply
- Modulator
- Treatment Head

WHAT KIND OF POWER SOURCE IS NEEDED FOR LINEAR ACCELERATORS?

1. Why not DC?
   - Problems of electrical breakdown; physical size of electrical equipment
2. Apply technique of repeated pulses, viz.

$$V \approx n\,v$$

   - need oscillating form of power supply
3. Leads to principle of cyclic and linear accelerators

WHAT KIND OF POWER SOURCE IS NEEDED FOR LINEAR ACCELERATORS?

4. Wavelength has to be short enough to accelerate electrons in a reasonable distance

5. S band microwave technology, developed for radar in WWII, has a frequency ~ 3 GHz, or $\lambda \approx 10$ cm

6. High power is also needed to ensure sufficient energy gain per cycle.

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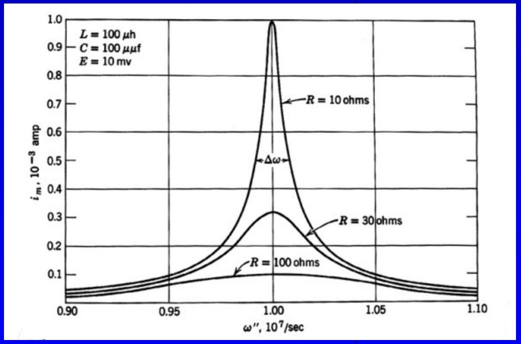
GENERATION OF HIGH POWER MICROWAVE PULSES

1. At high frequencies, ordinary circuits become impractical
   (radiation loss, skin effect)
2. Hollow cavities as a form of resonant circuit
3. The quality factor, or Q value, of a resonant circuit or cavity is defined as

$$Q = \frac{Energy\ stored\ in\ cycle}{Energy\ lost\ per\ cycle}$$



For a circuit, Q = 10^2, whereas for cavity, Q = 10^4

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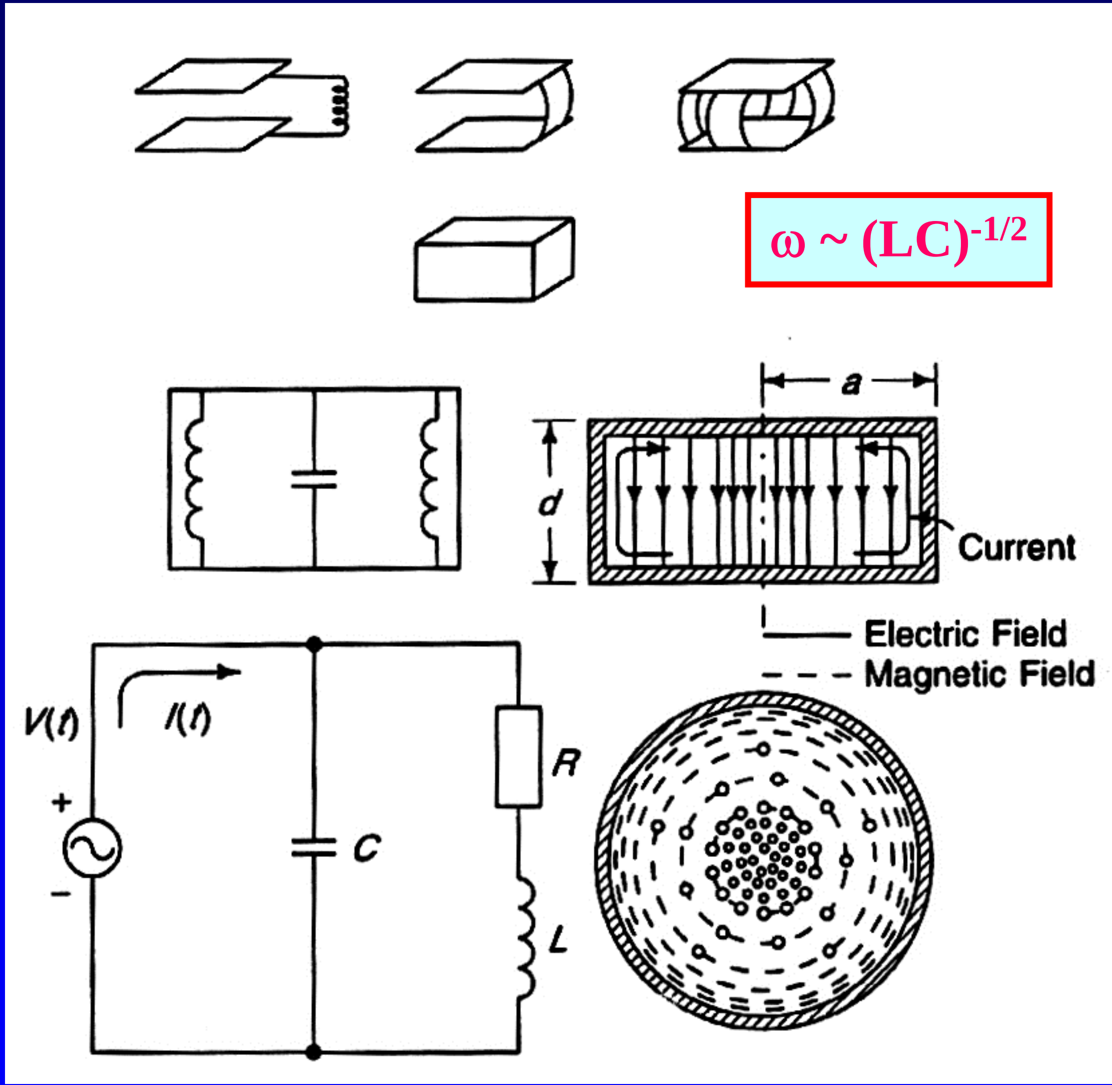
Cavity Principle



$\omega \sim (LC)^{-1/2}$

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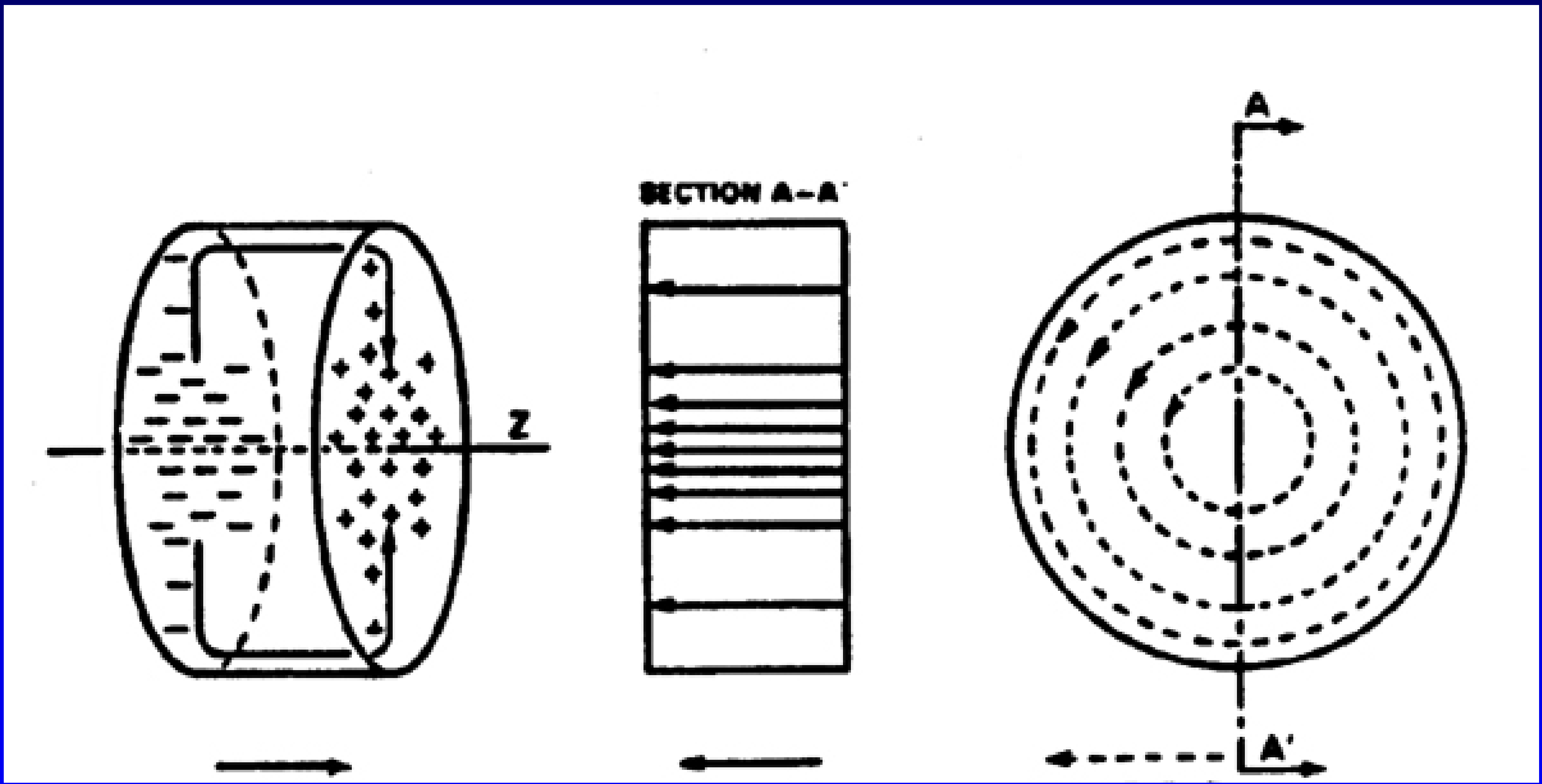
GENERATION OF HIGH POWER MICROWAVE PULSES

1. Achieved through devices called magnetrons and klystrons

2. To understand these devices, need to consider properties of cavity resonators

3. Cavity resonators feature in both power sources and accelerating structures

Cavity Principle - I



Current Charge **E-field** **H-field**

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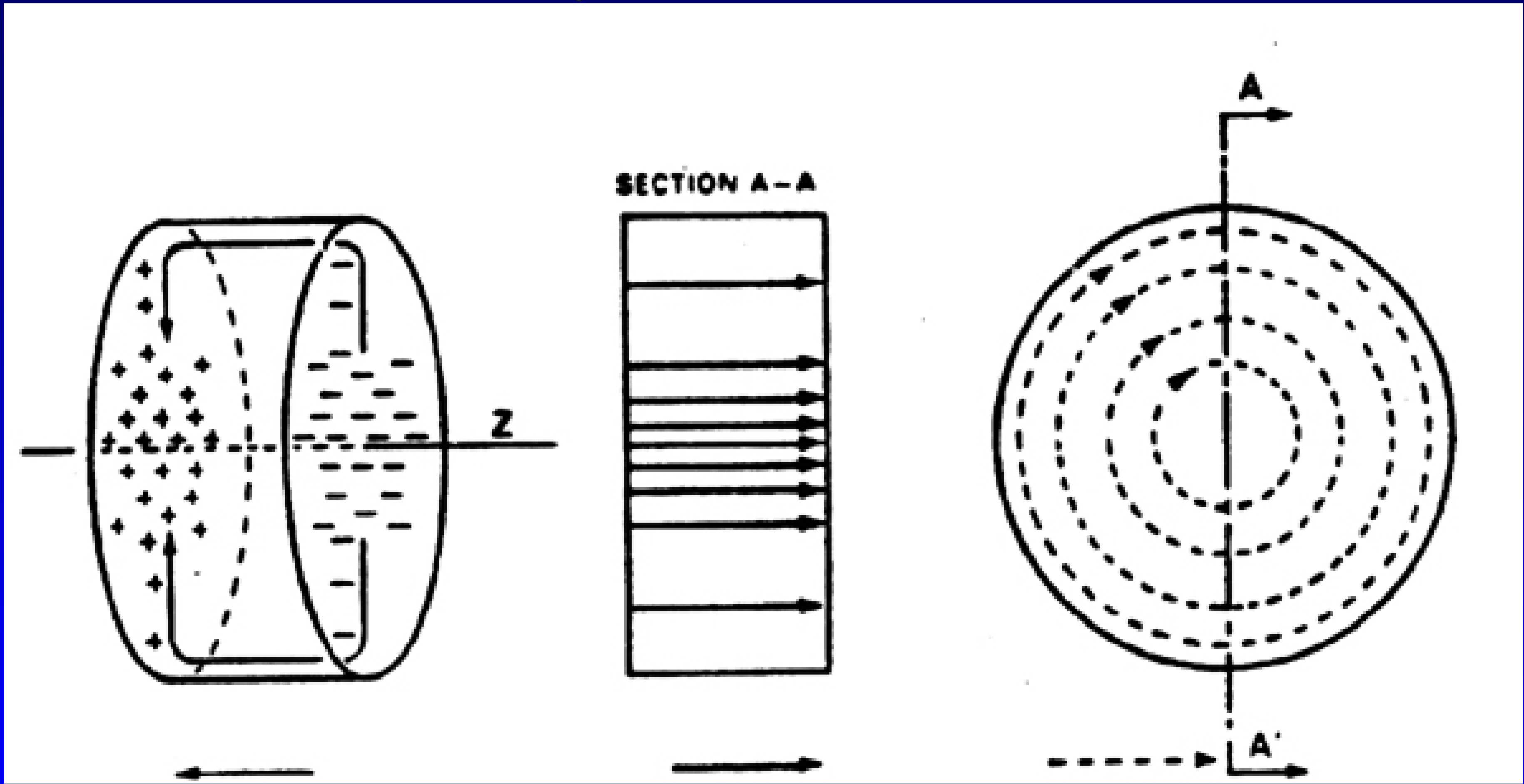
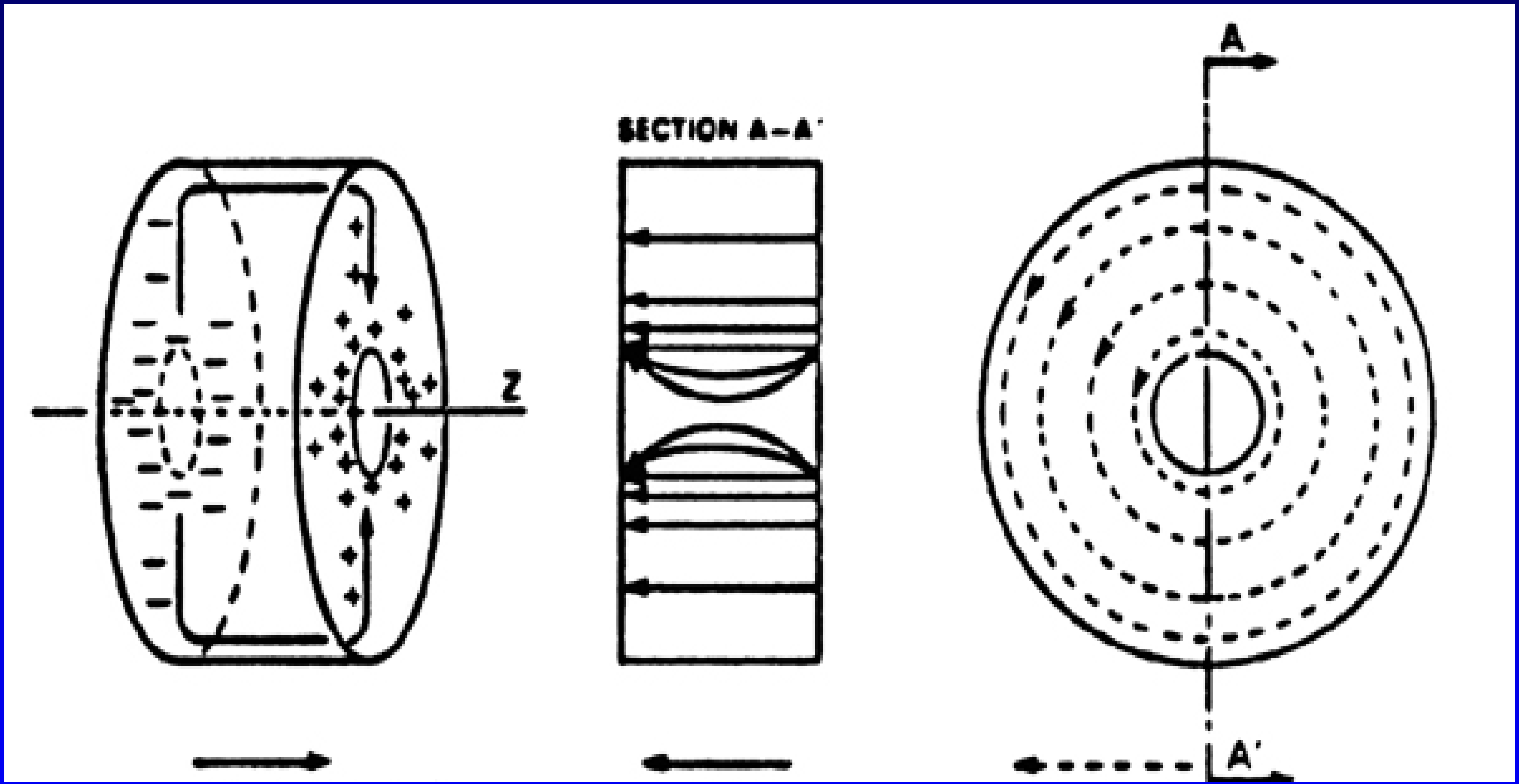
Cavity Principle - II



Current Charge **E-Field** **B-Field**

Cavity Principle - III



Current Charge **E-field** **B-field**

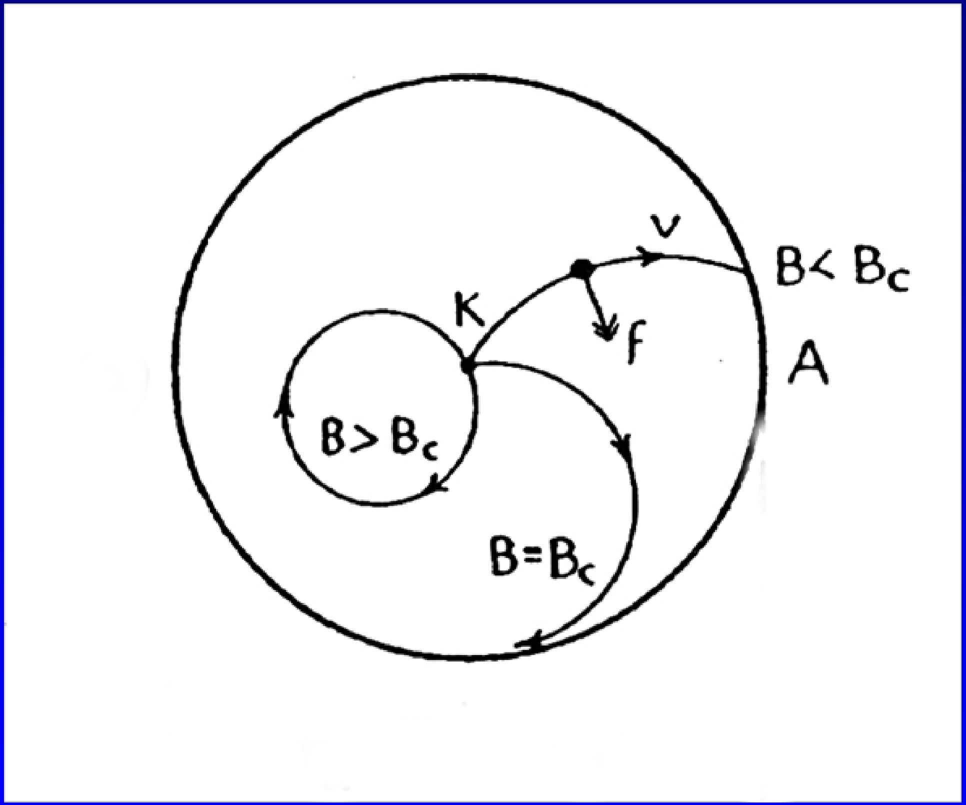
ROLE OF RESONANT CAVITIES IN LINEAR ACCELERATORS

1. Cavity acts as an acceleration module

2. Multiple cavity arrangement can act as RF amplifier
   - klystron

3. Multiple cavity arrangement can act as a high power oscillator
   - magnetron

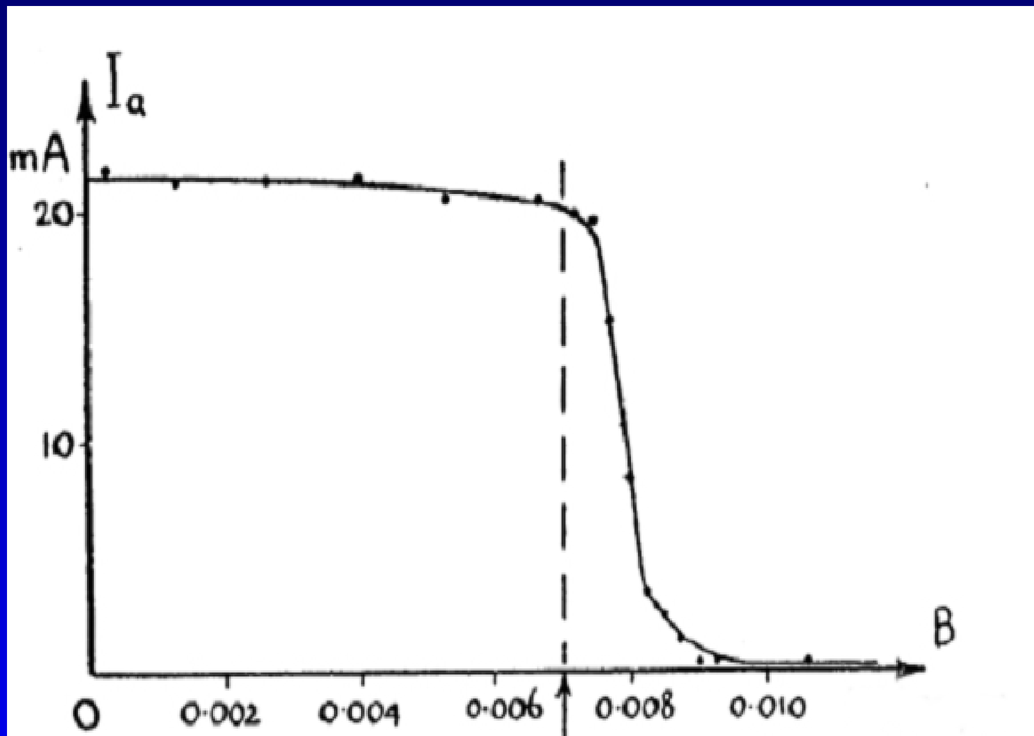
Magnetron Principle



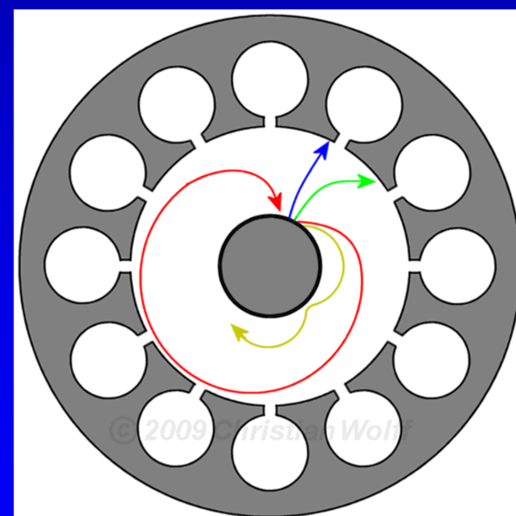
Illustrating the theory of the cylindrical magnetron

B_c depends on electron velocity and hence accelerating voltage

Magnetron Principle - II



Increasing the magnetic field eventually leads to a sudden drop in current



Theoretical Cut-off value

100 Gauss

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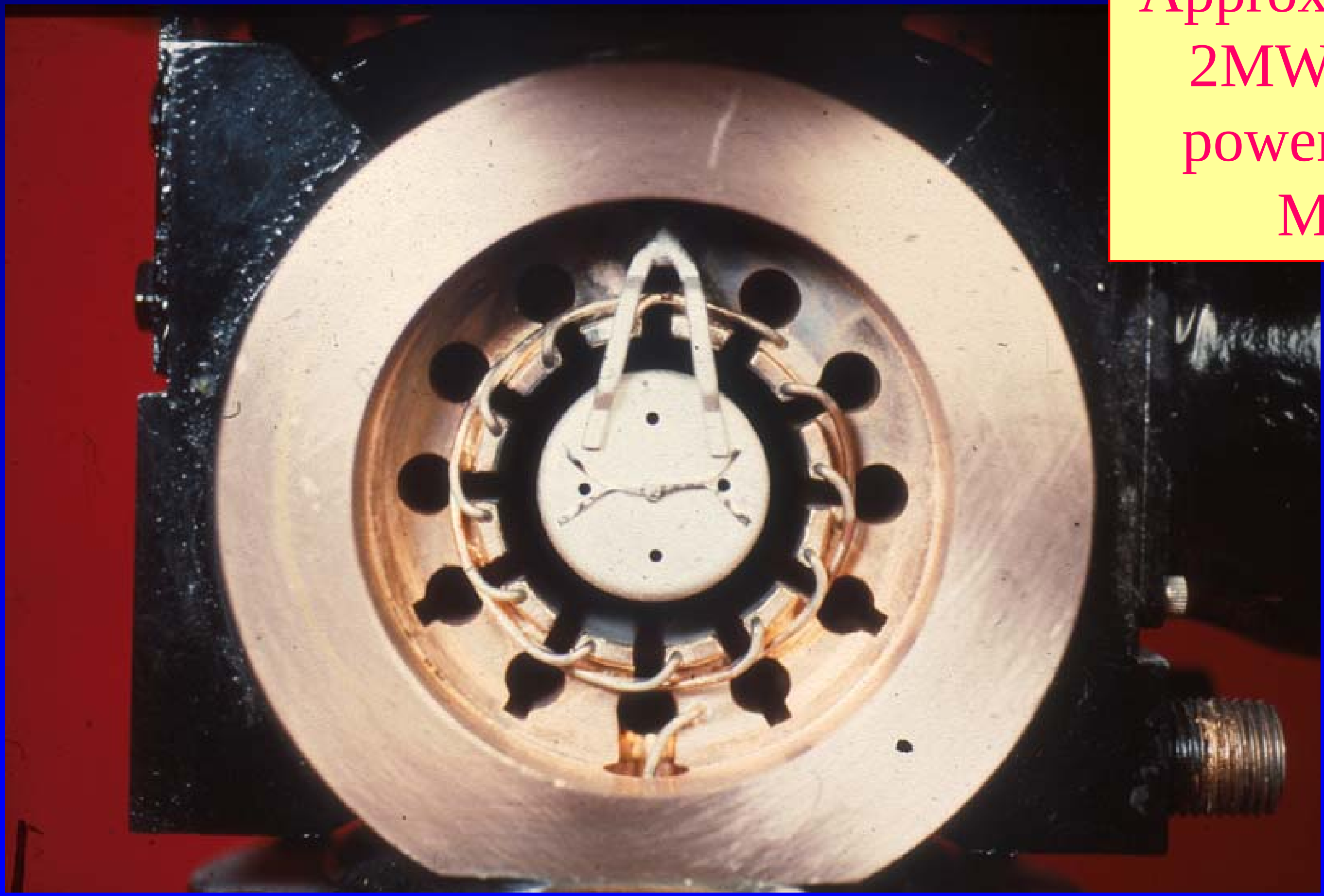
Magnetron - Detail



Approximately 2MW peak power for 4 MV

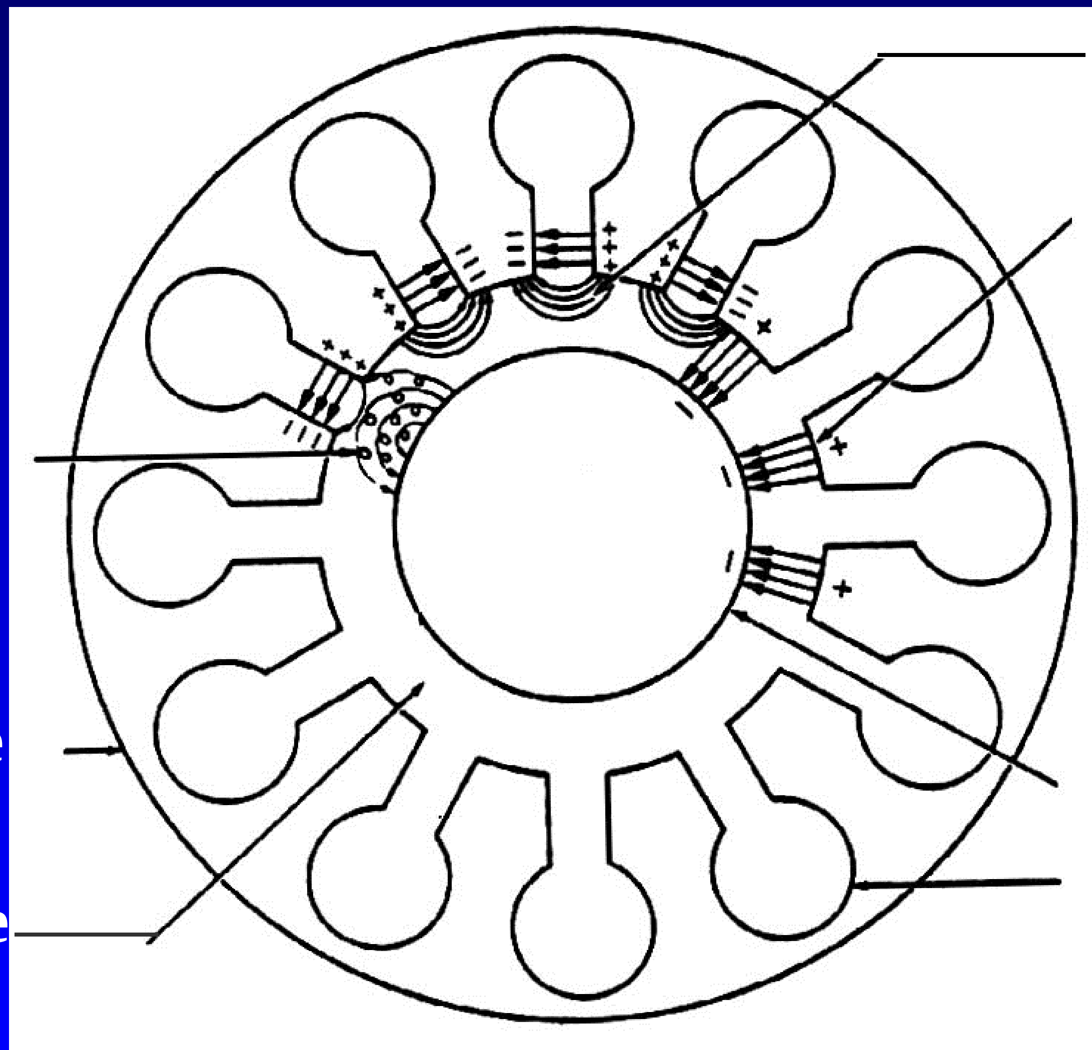
Magnetron Action -I

Charge +,-
From E_p
Charge +,-
From E_m

S

Anode

Drift Space



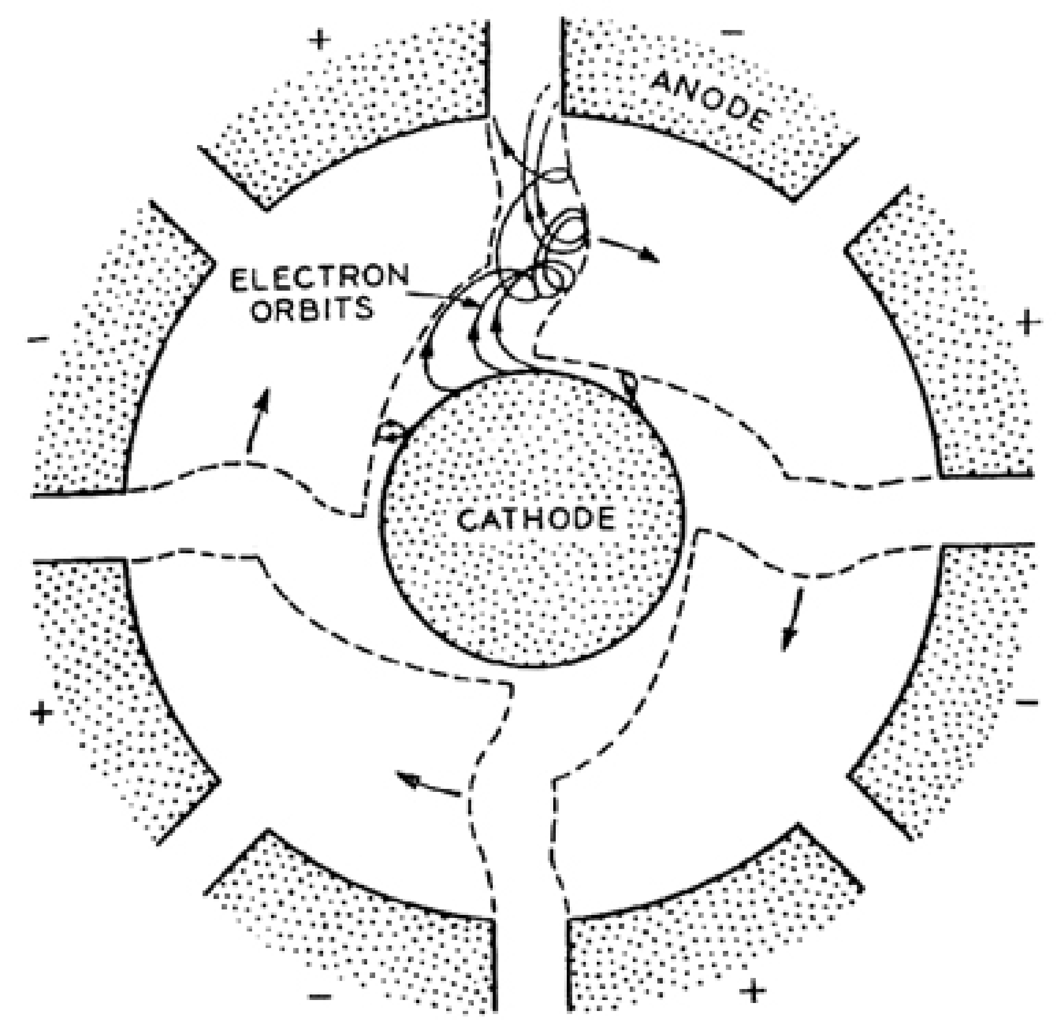
E_m

E_p

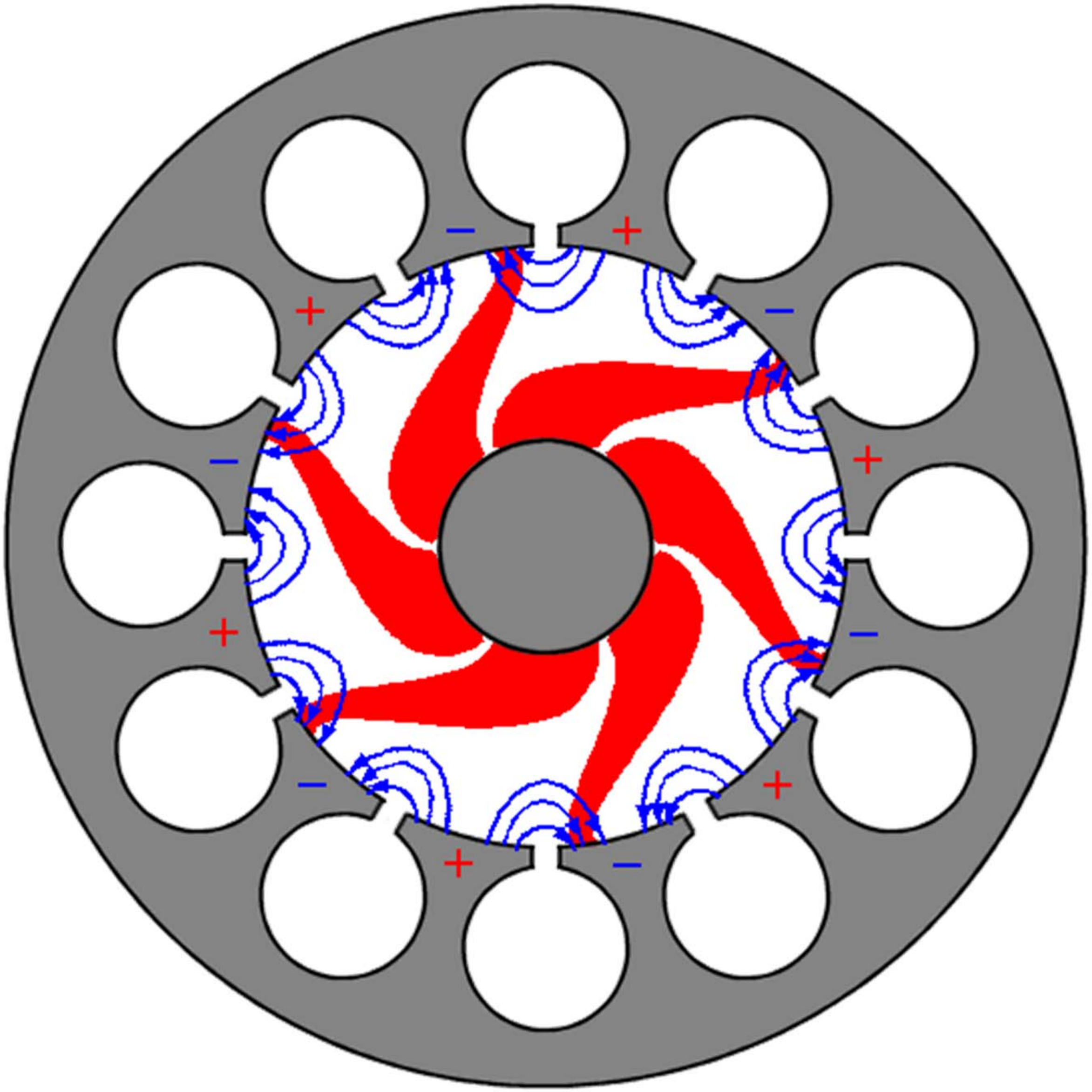
Cathode

Cavity

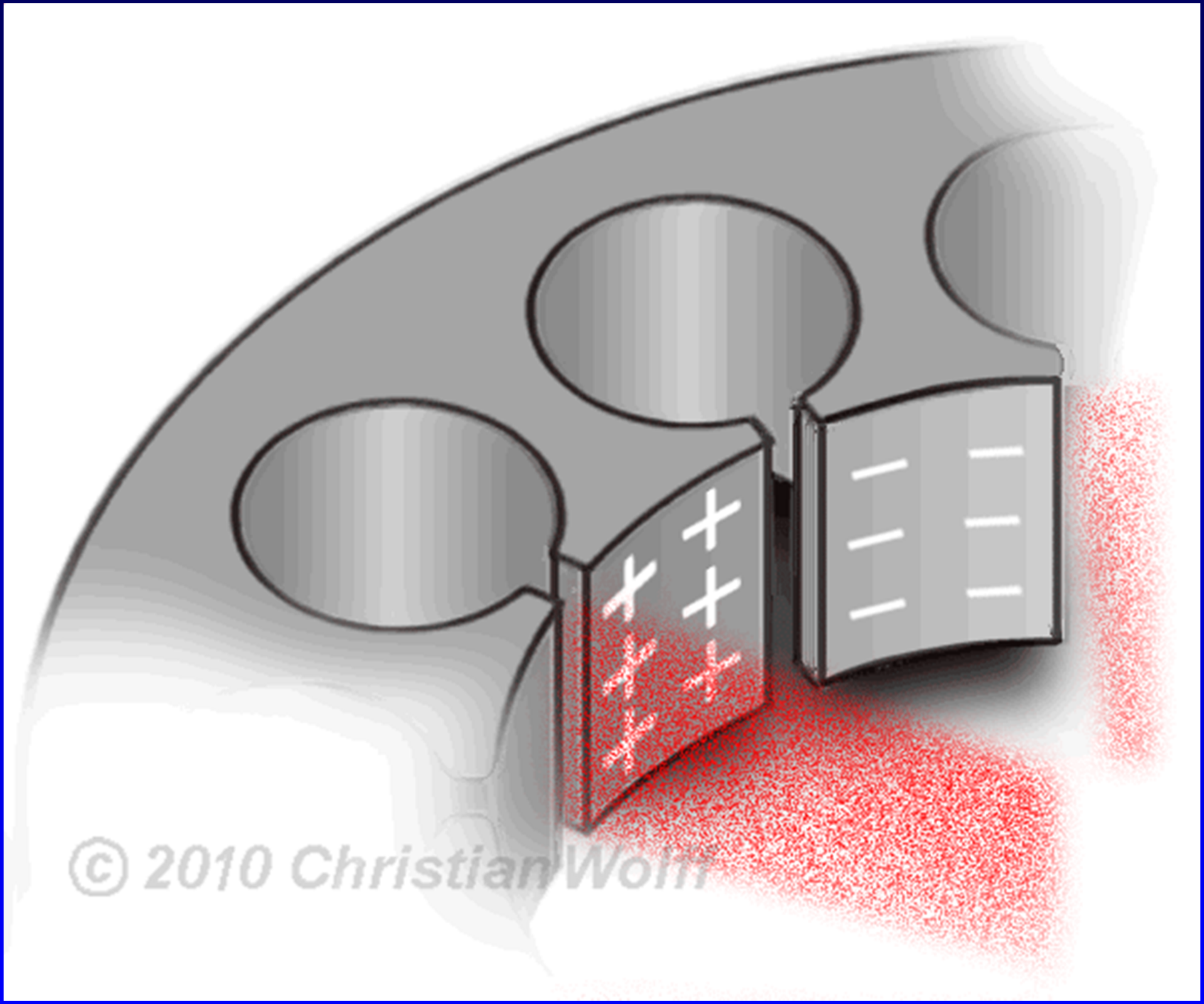
Magnetron Action - III



Space-Charge distribution and electron paths in an 8-cavity magnetron, when oscillating.

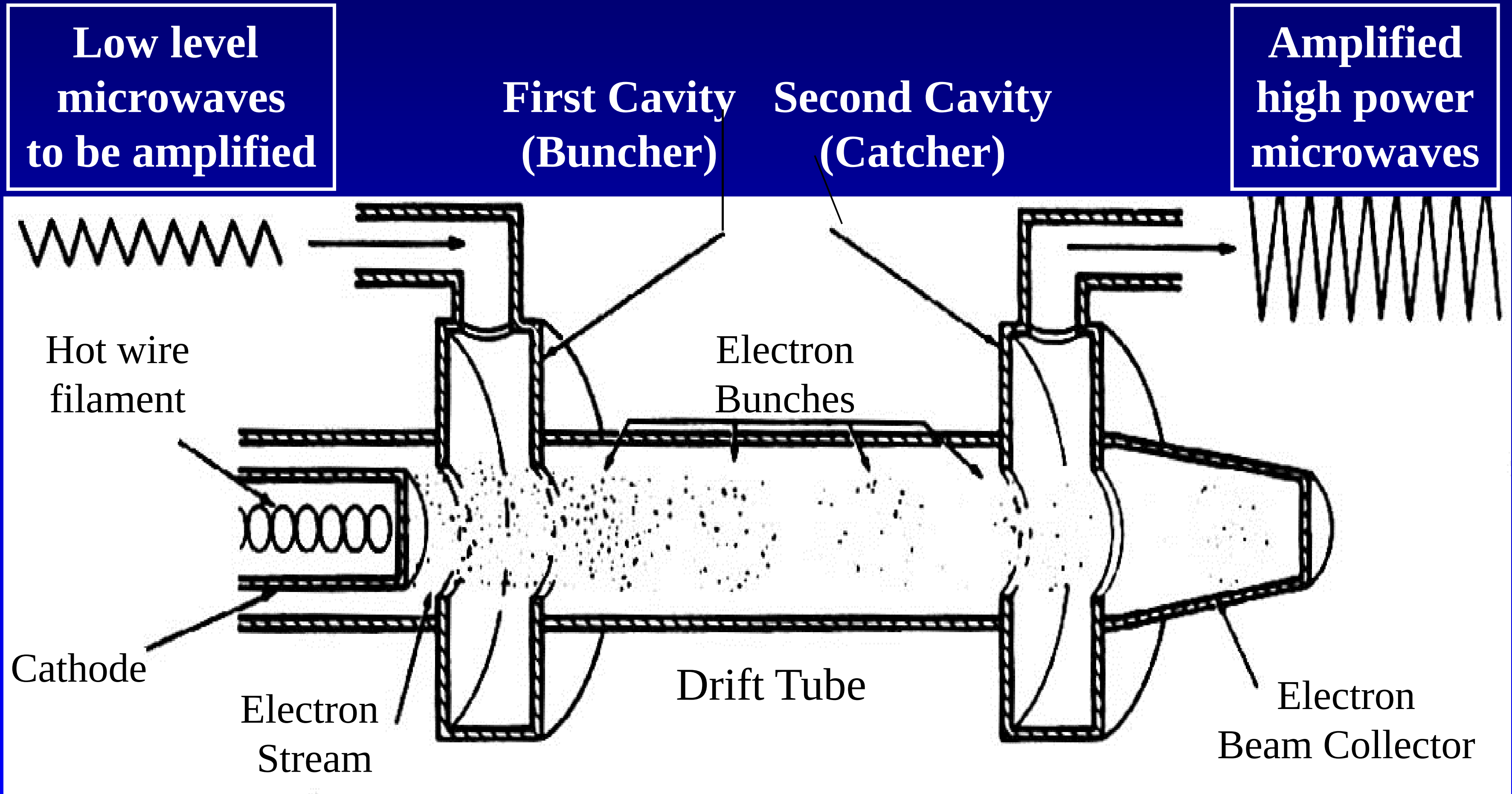


Slide courtesy of Christian Wolff

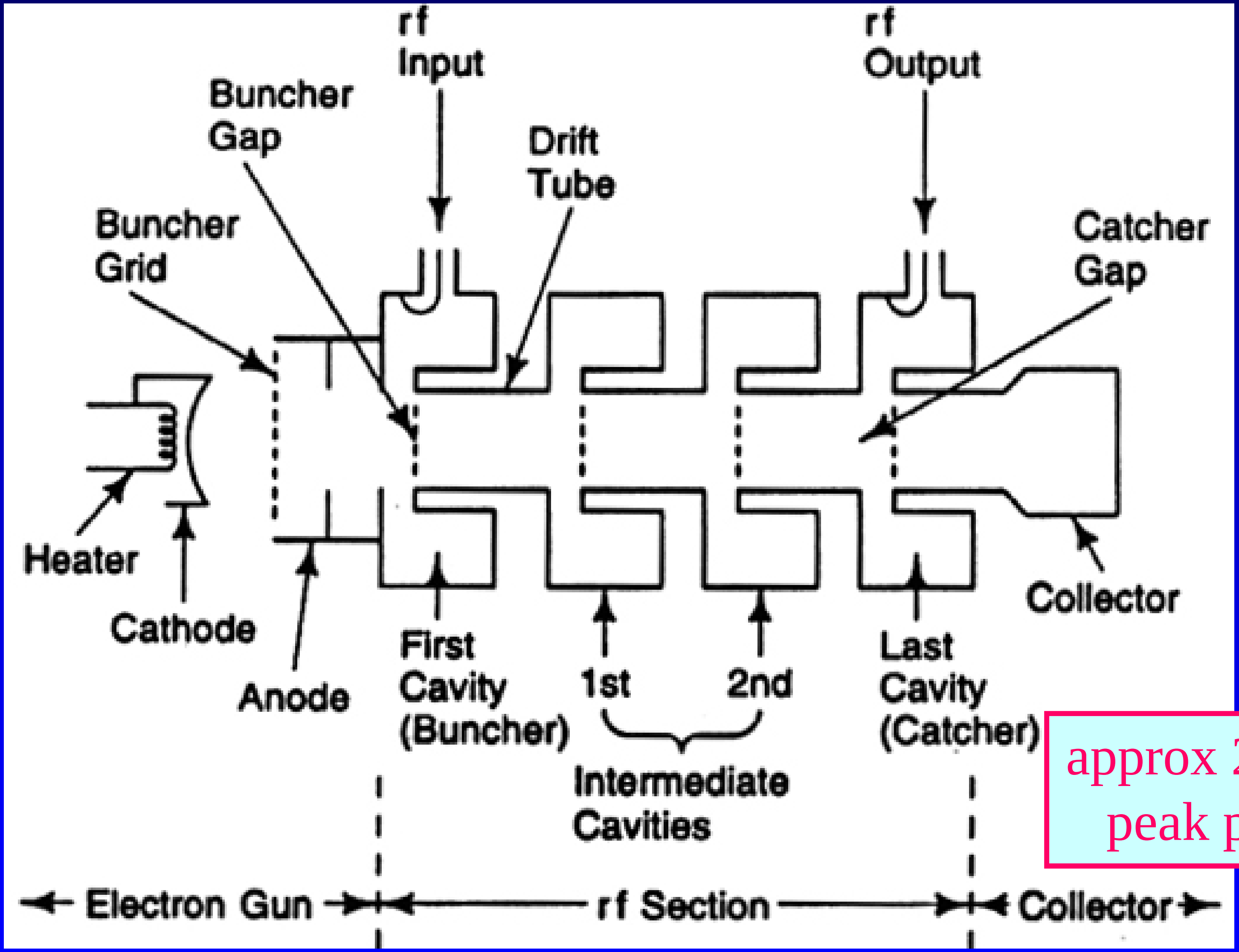


Christian Wolff: www.radartutorial.eu

Principle of Klystron

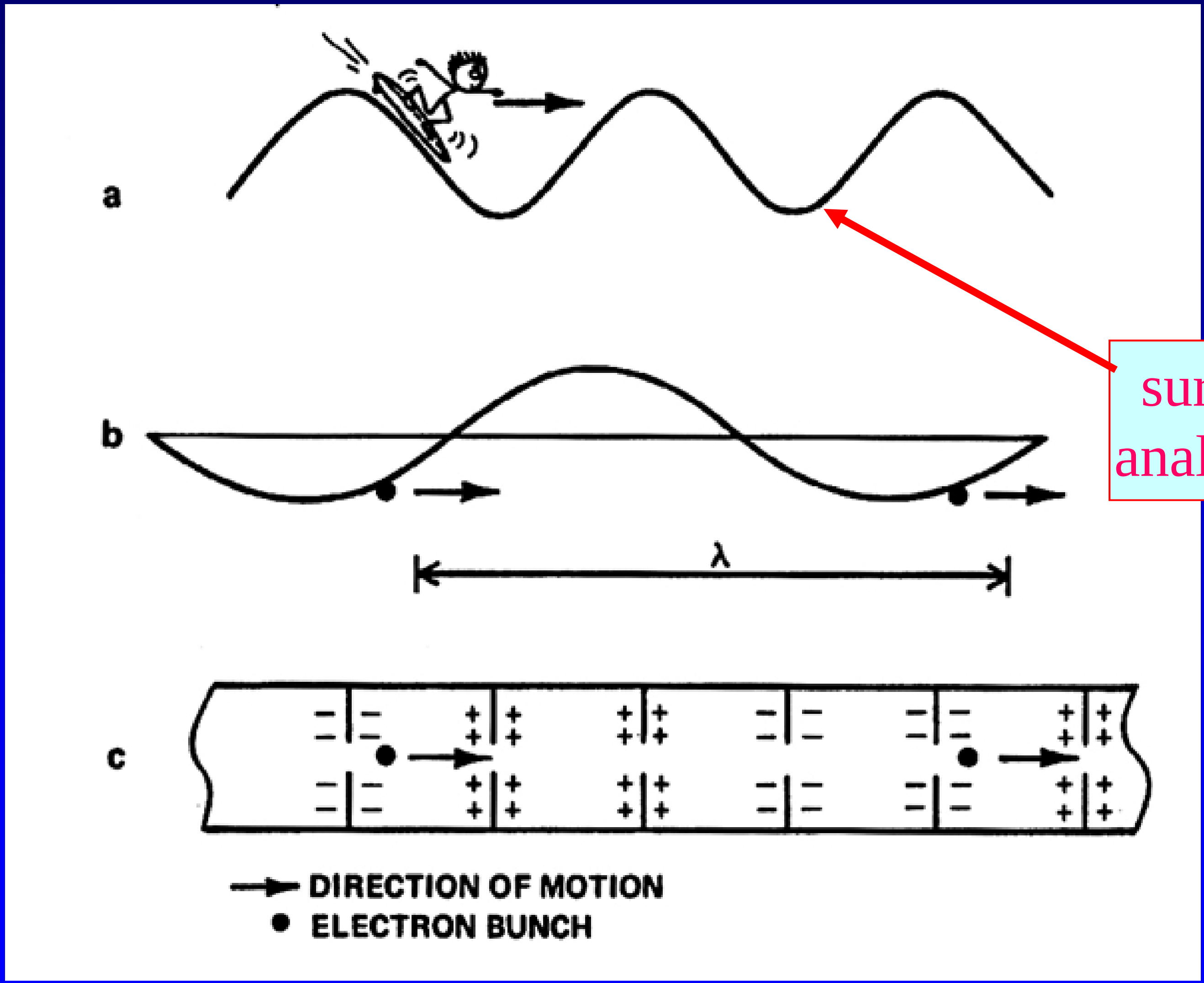


Klystron with Four Sections



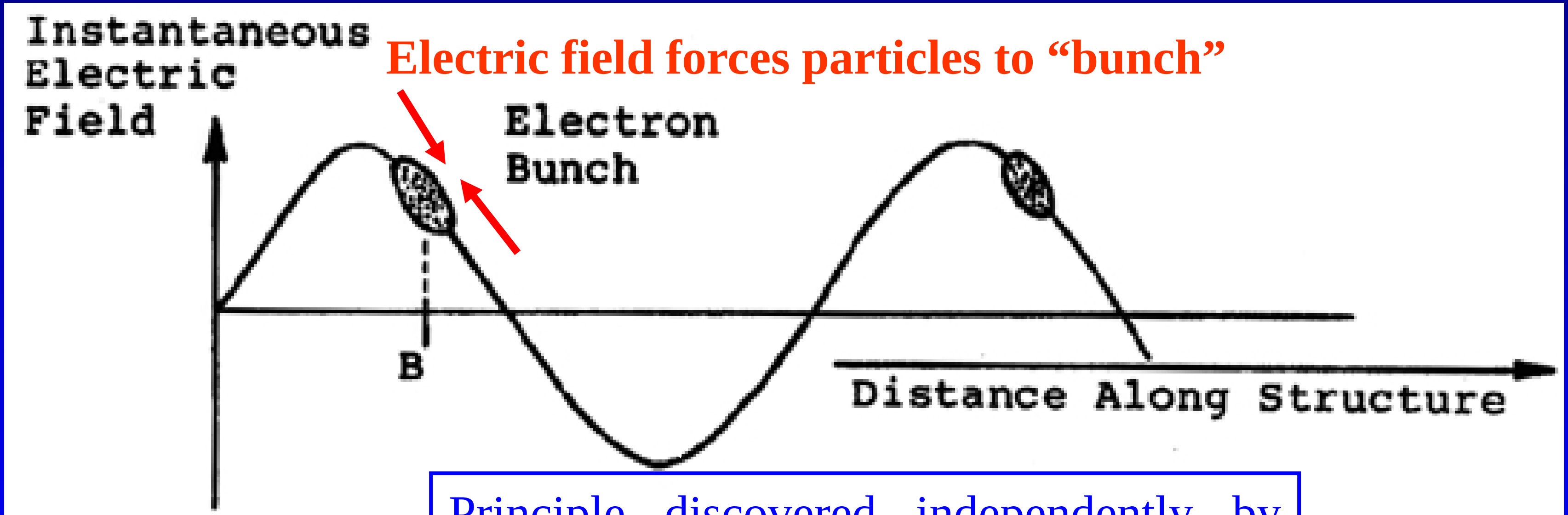
approx 20 MW
peak power

Acceleration Principle of Waveguide



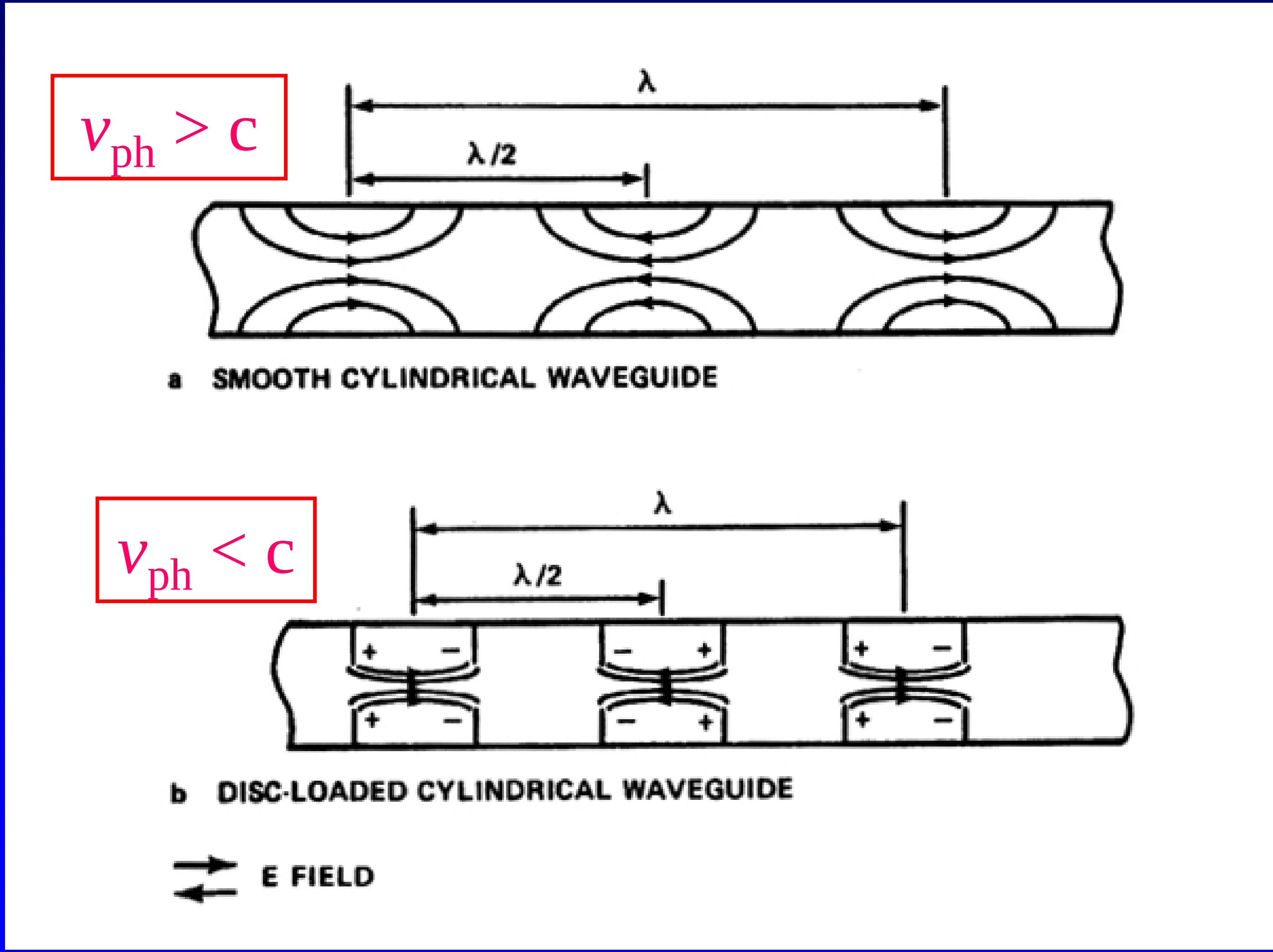
surfing analogy !

Principle of Phase Stability

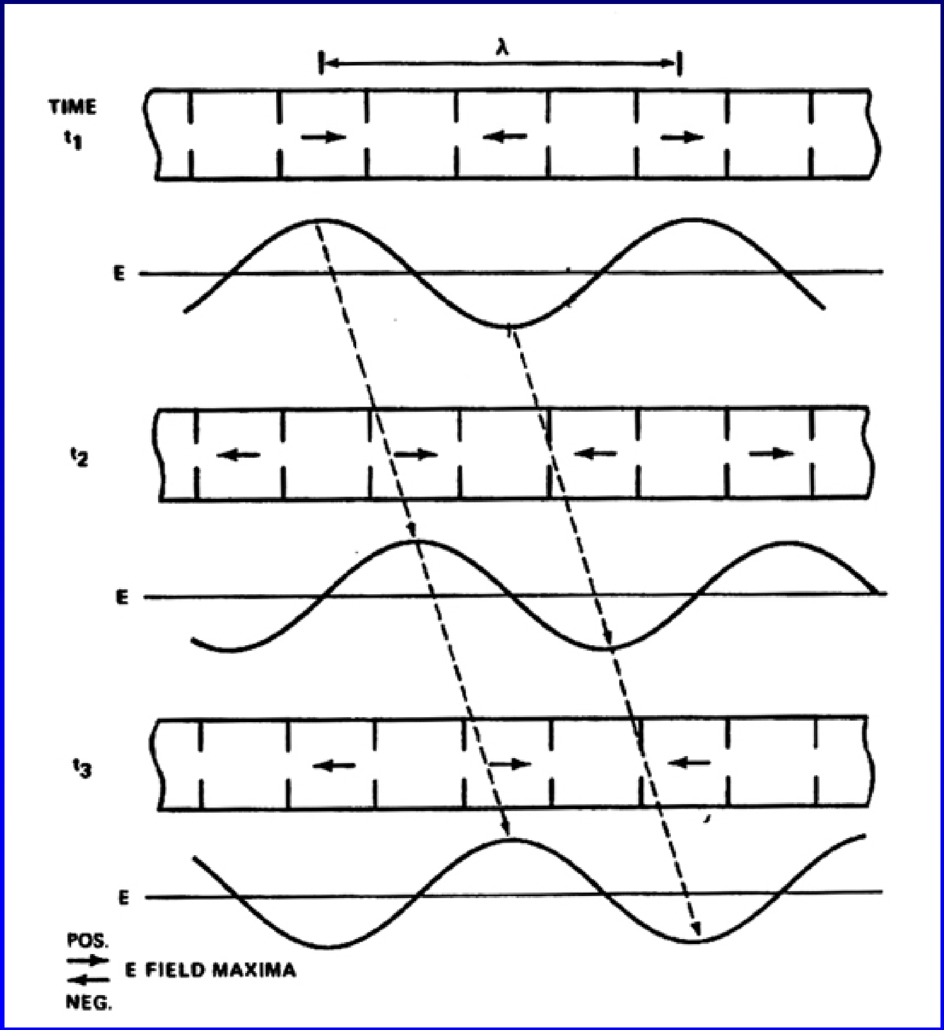


Principle discovered independently by Veksler (1944) and McMillan (1945)

Disc-Loaded Waveguide



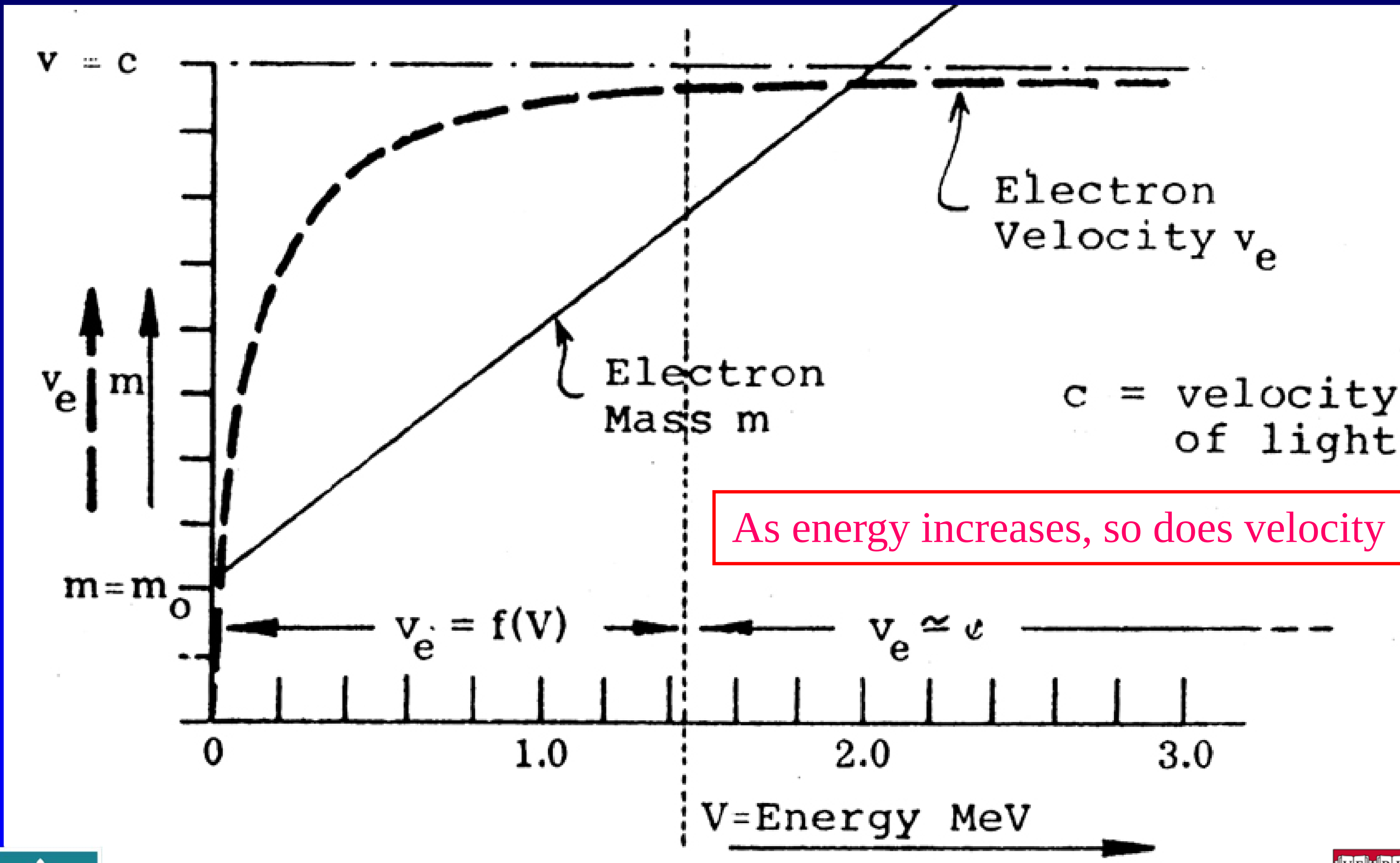
Travelling Waveguide



the amplitude of the e/m wave progressively decreases along the guide

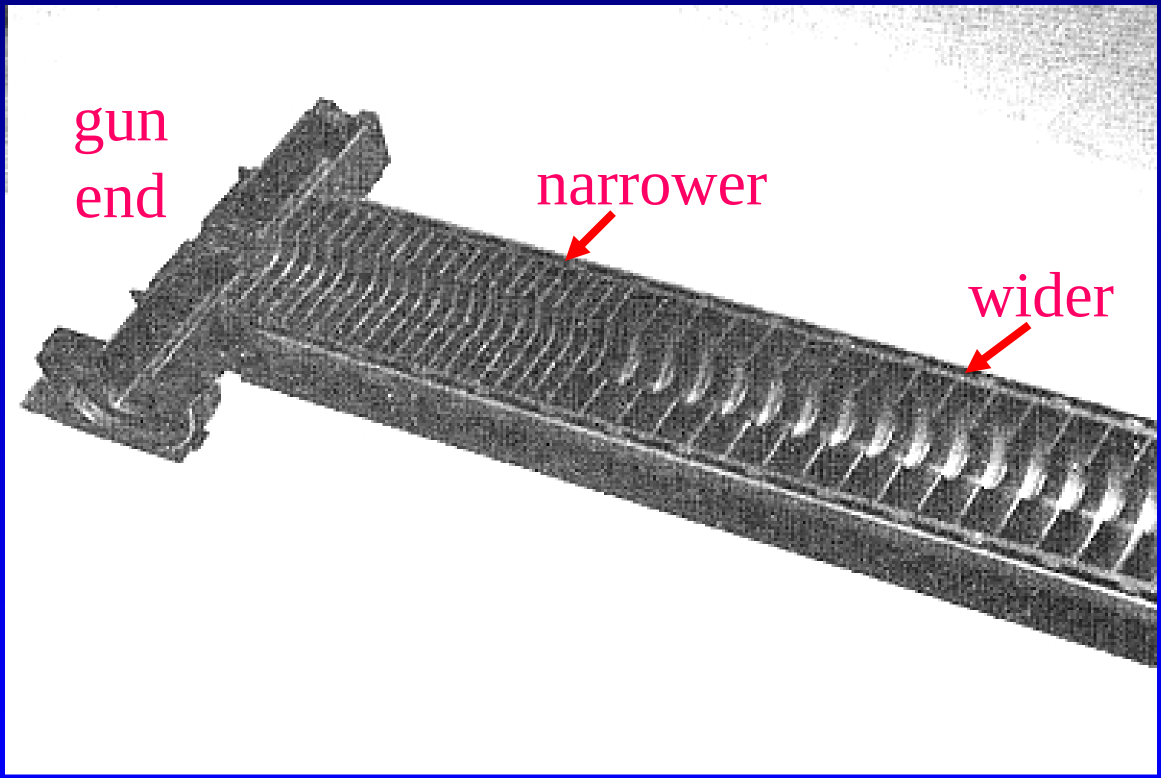
Remaining beam power is dumped at the end

Mass-Energy Relation for Electron

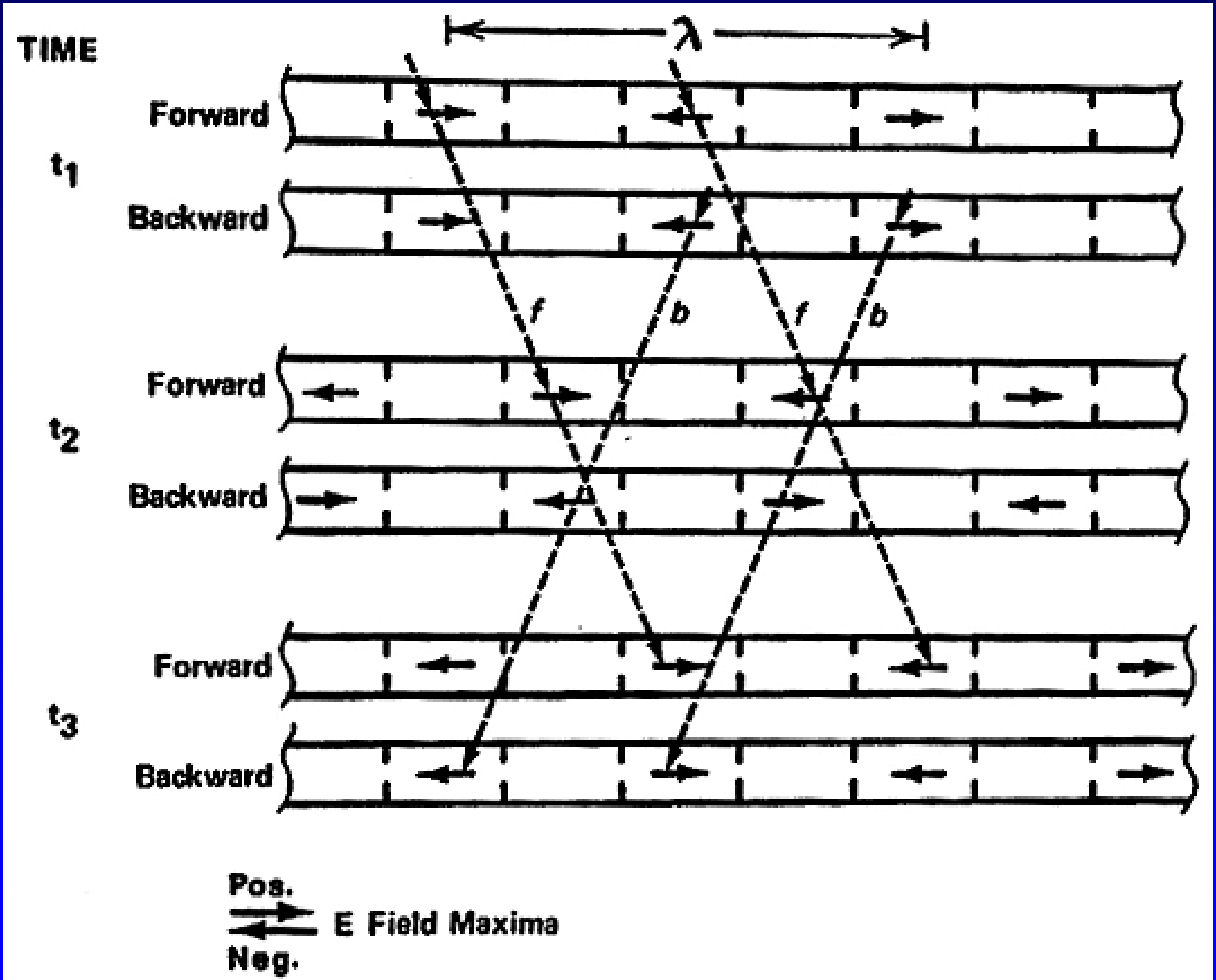


As energy increases, so does velocity

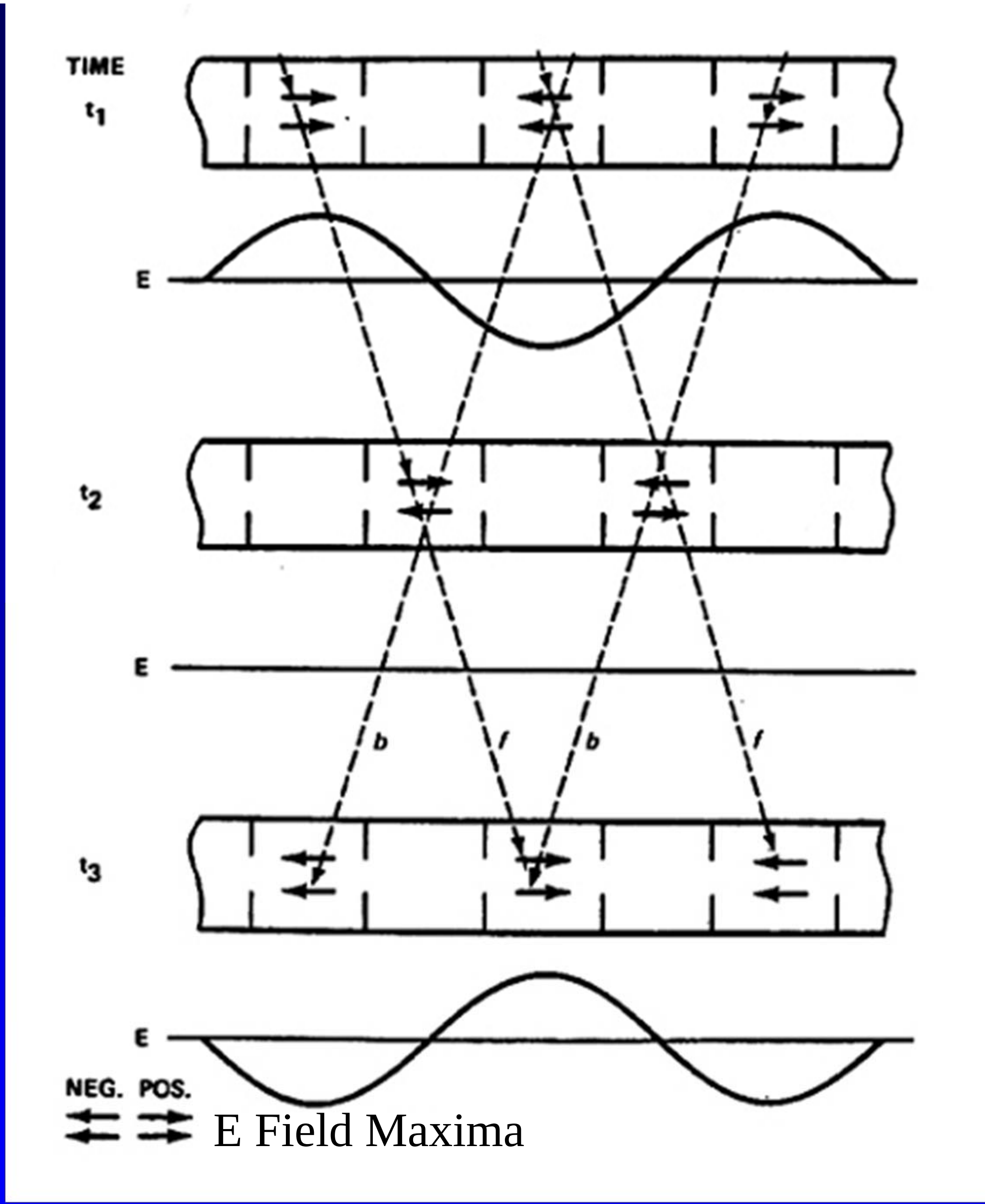
Cut-Away of Travelling Guide



Standing WG principle - I

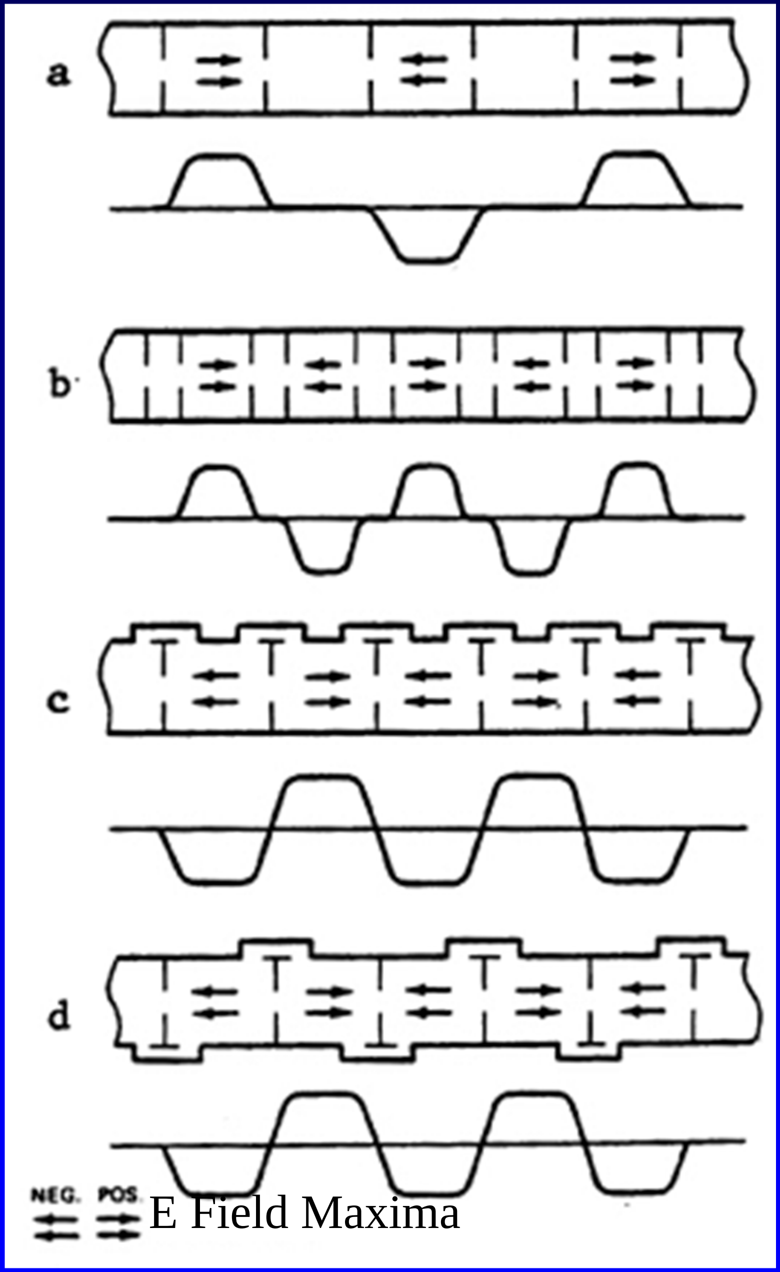


Standing WG principle - II

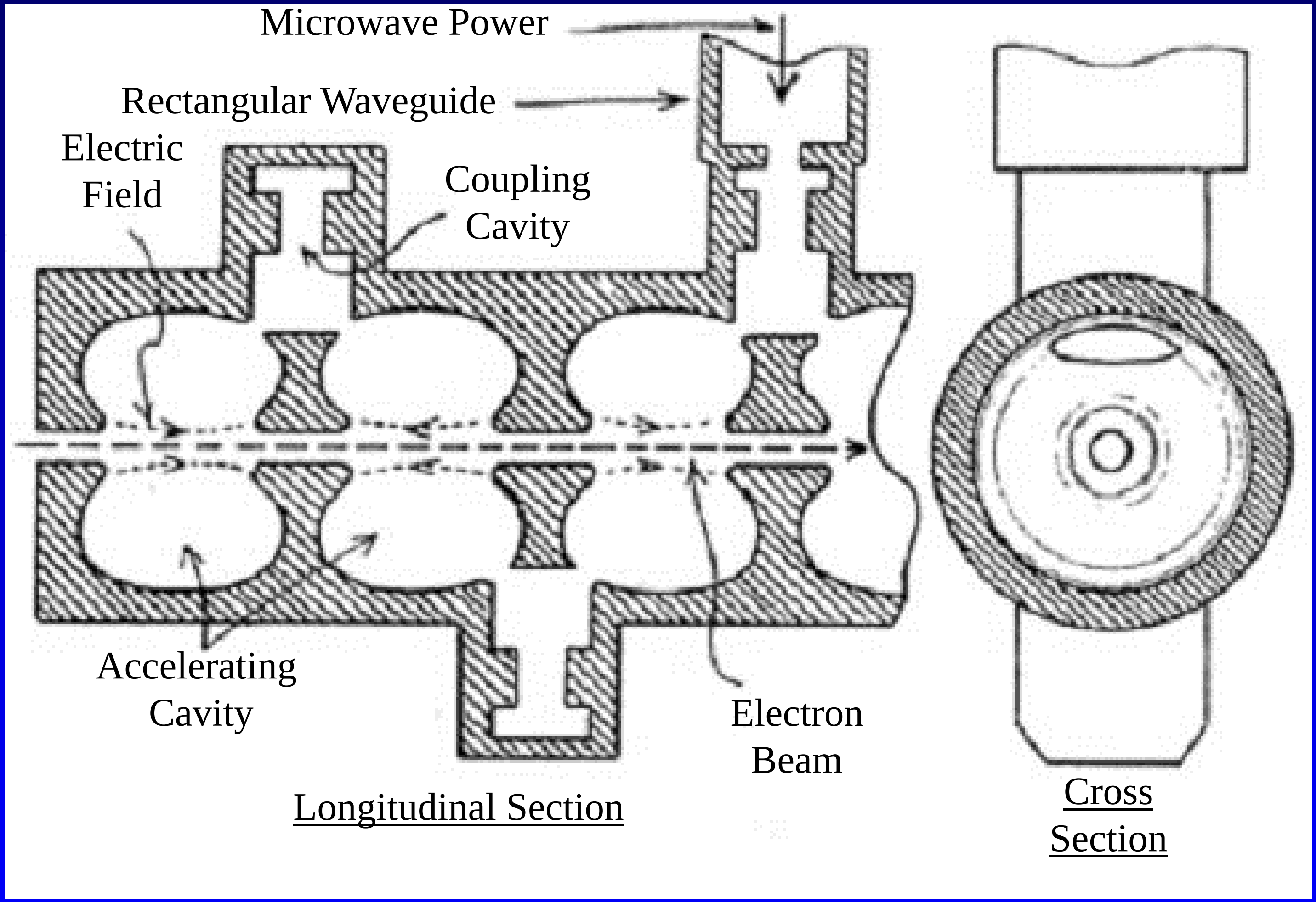


Standing WG principle - III

Note: the overall e/m amplitude decreases with beam loading

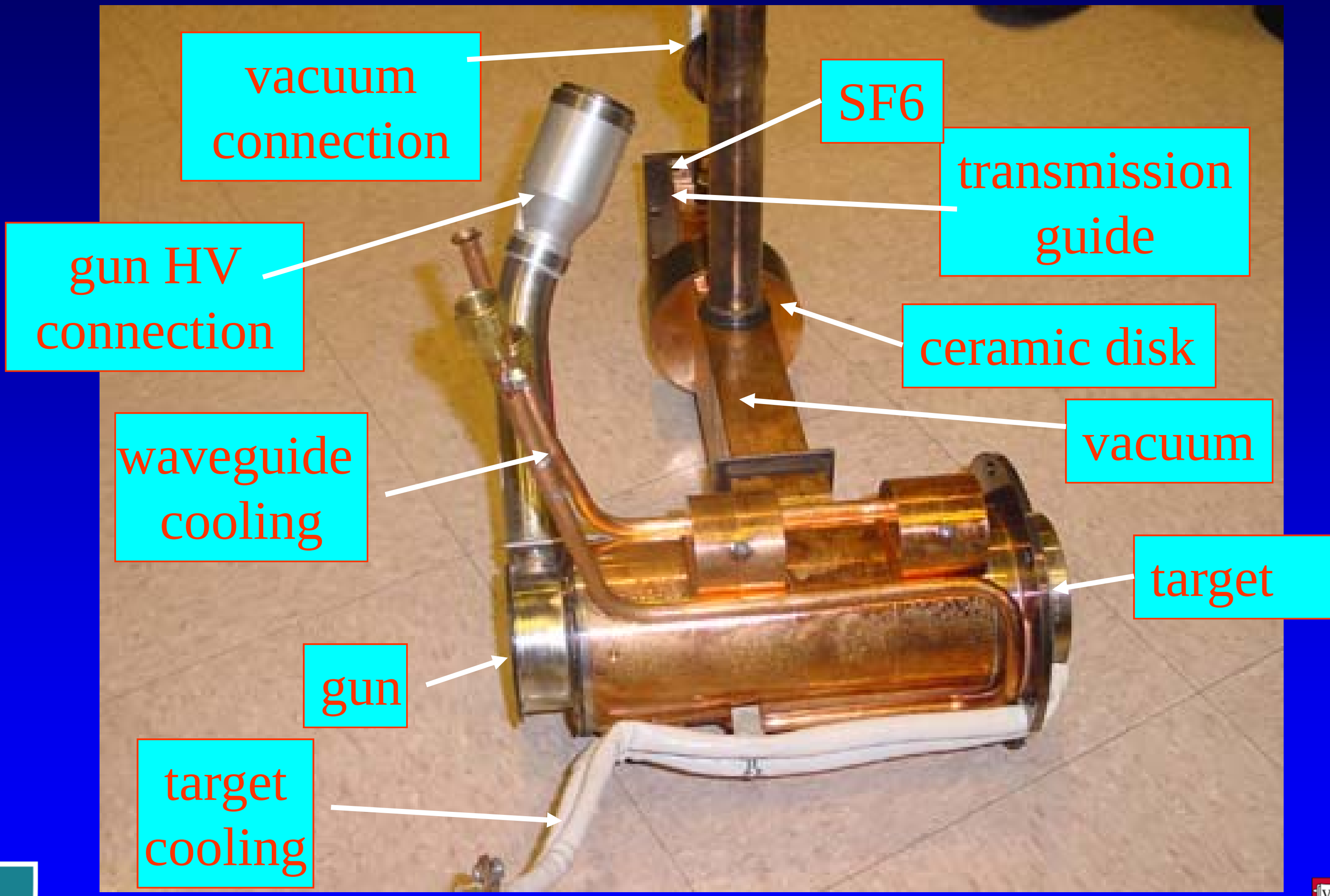


Standing WG - Schematic

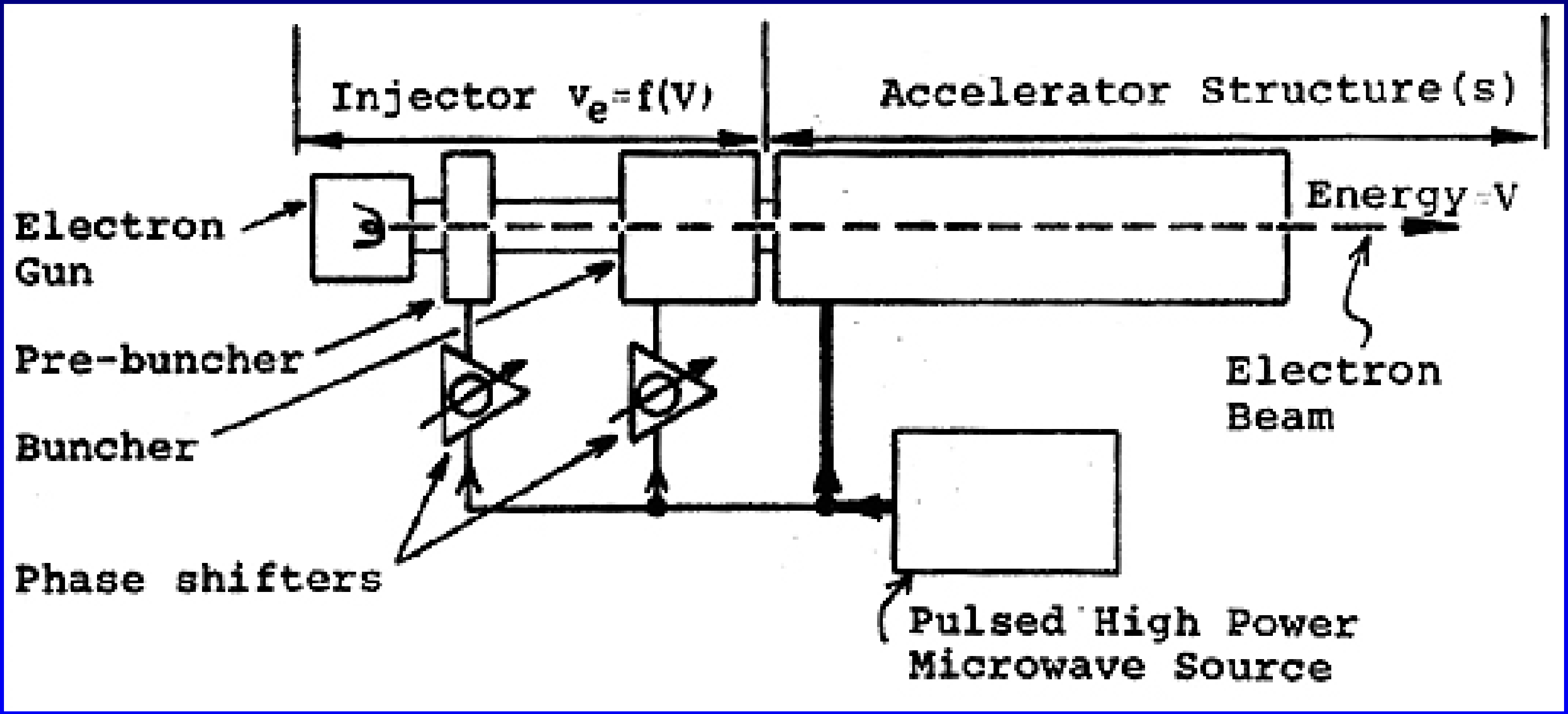


note that travelling waveguides are longer than standing waveguides due to side coupled cavities

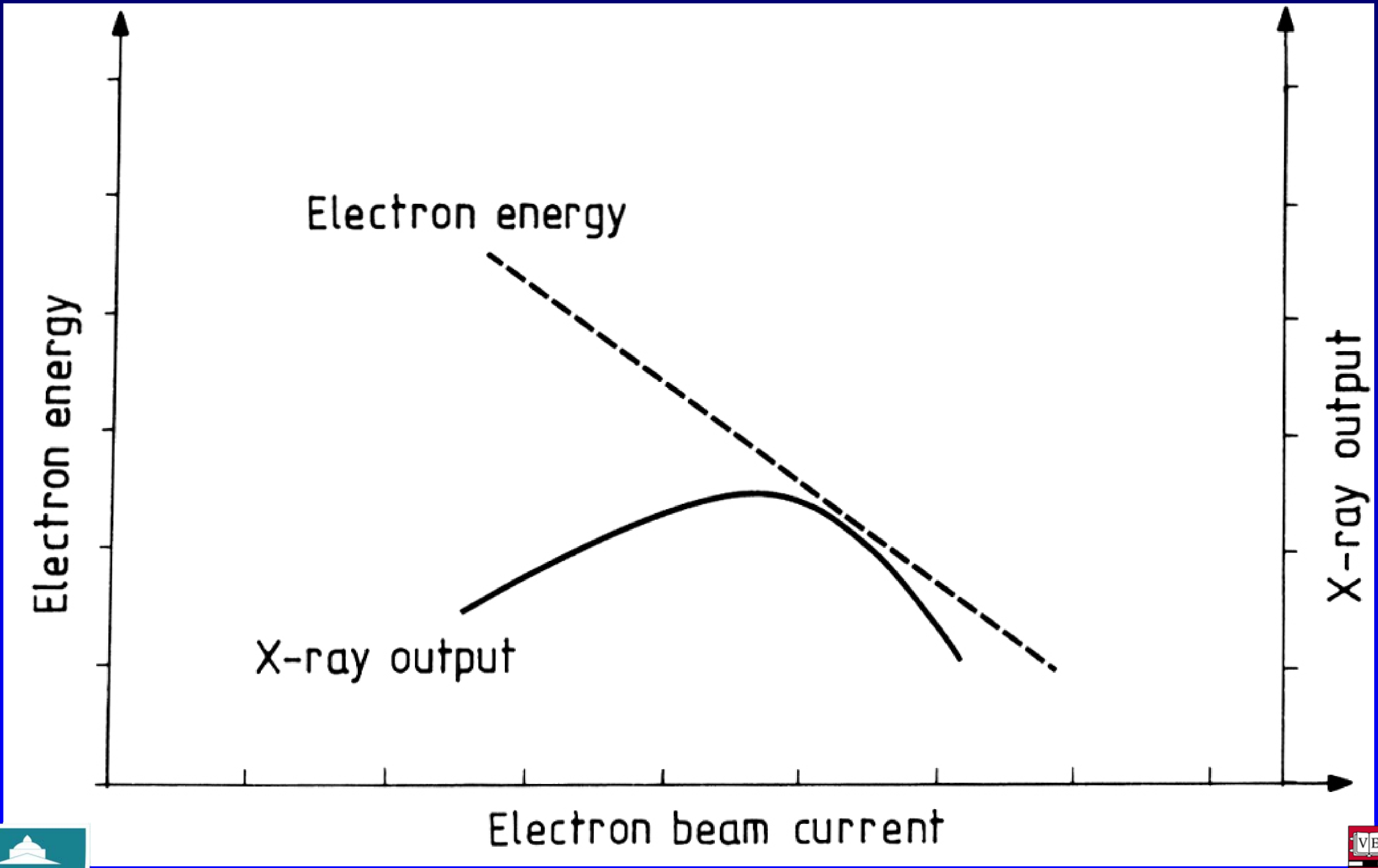
Waveguide for 4 MV Linac



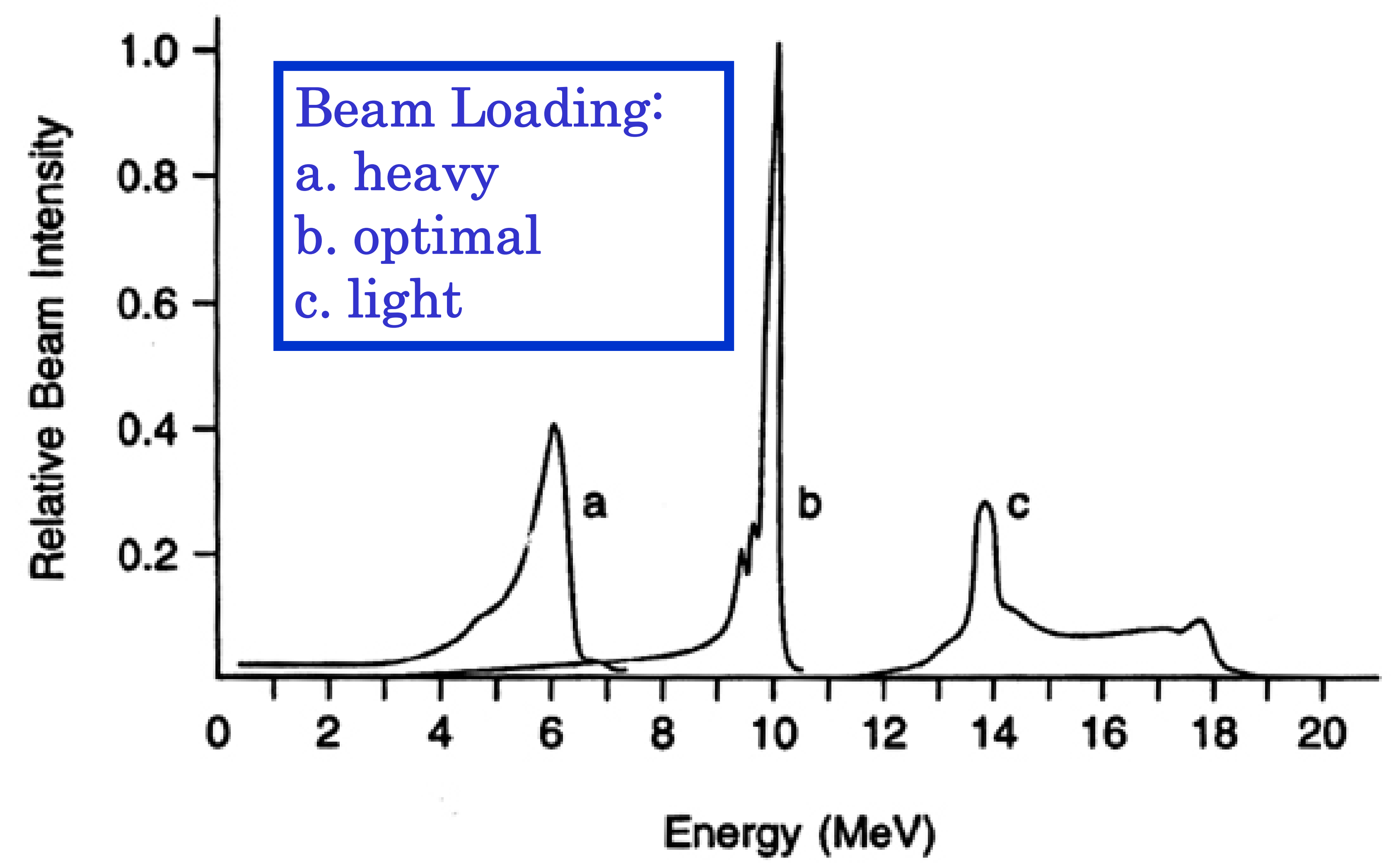
Schematic of Waveguide



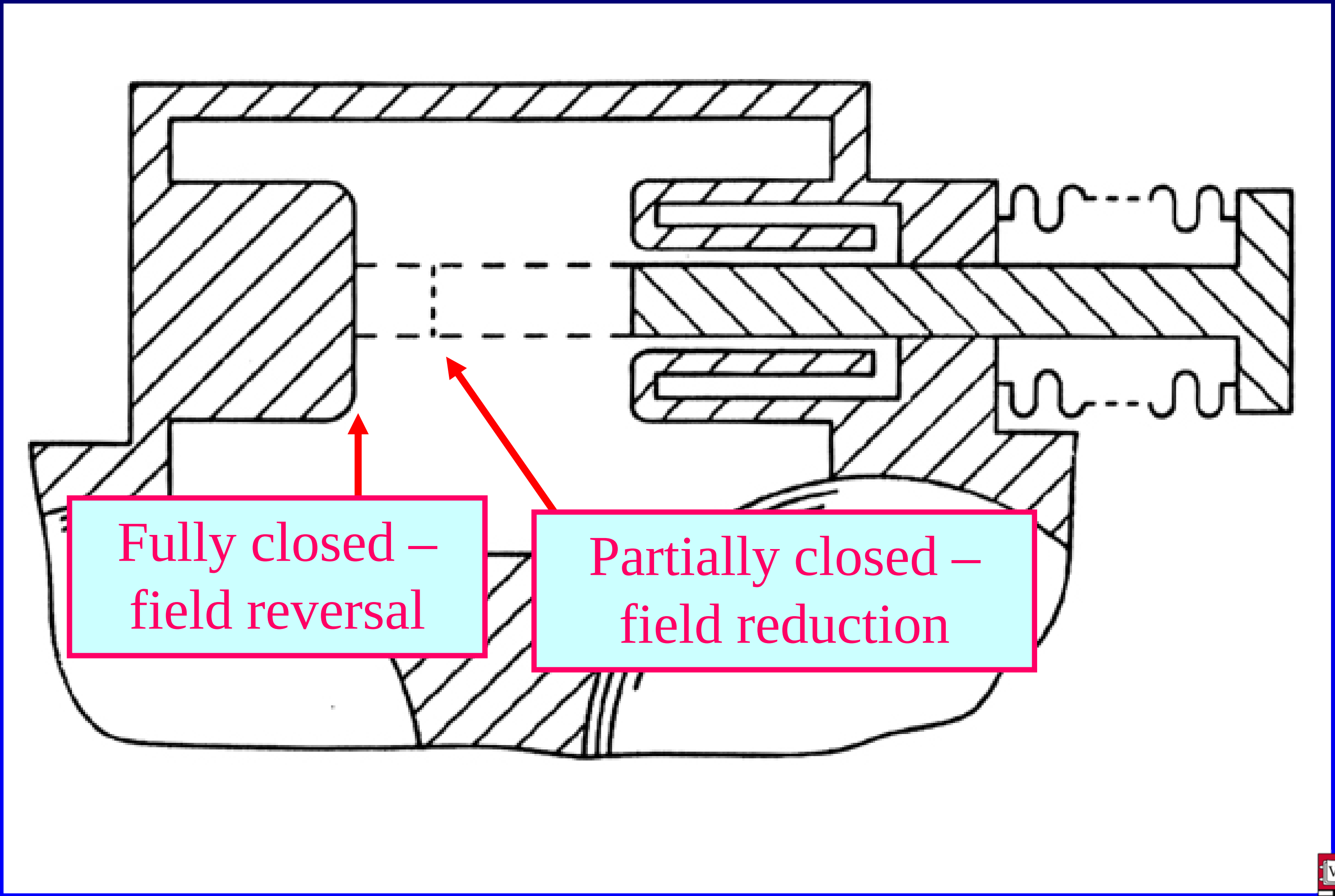
Electron Beam Current, X-Ray output vs. Electron Energy



X-Ray Output for Various Energies



Schematic of Energy Switch



Principle of Energy Switch

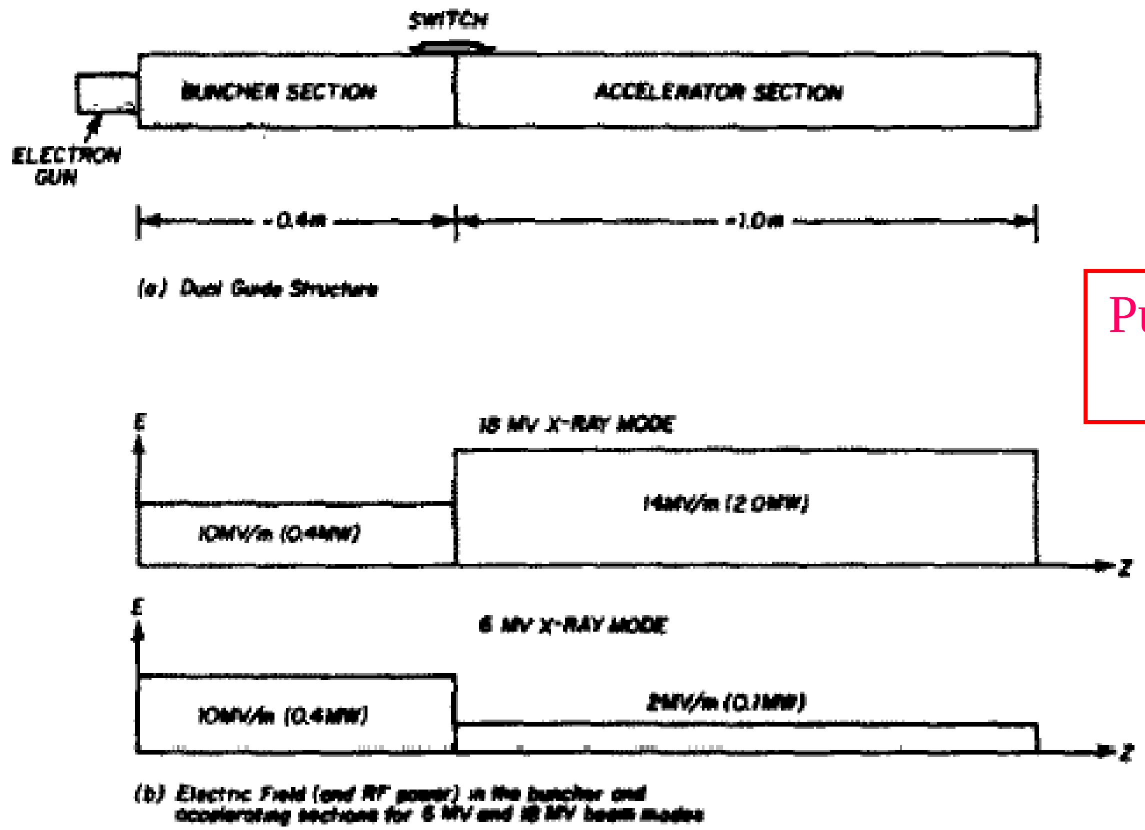


Fig. 2. Dual accelerator structure illustrating the switched-guide concept used on the Varian Clinac 1800.

Purdy & Goer, NIMRIP:B 11:1090-1095; 1985

Also used in the Mobetron IOERT machine

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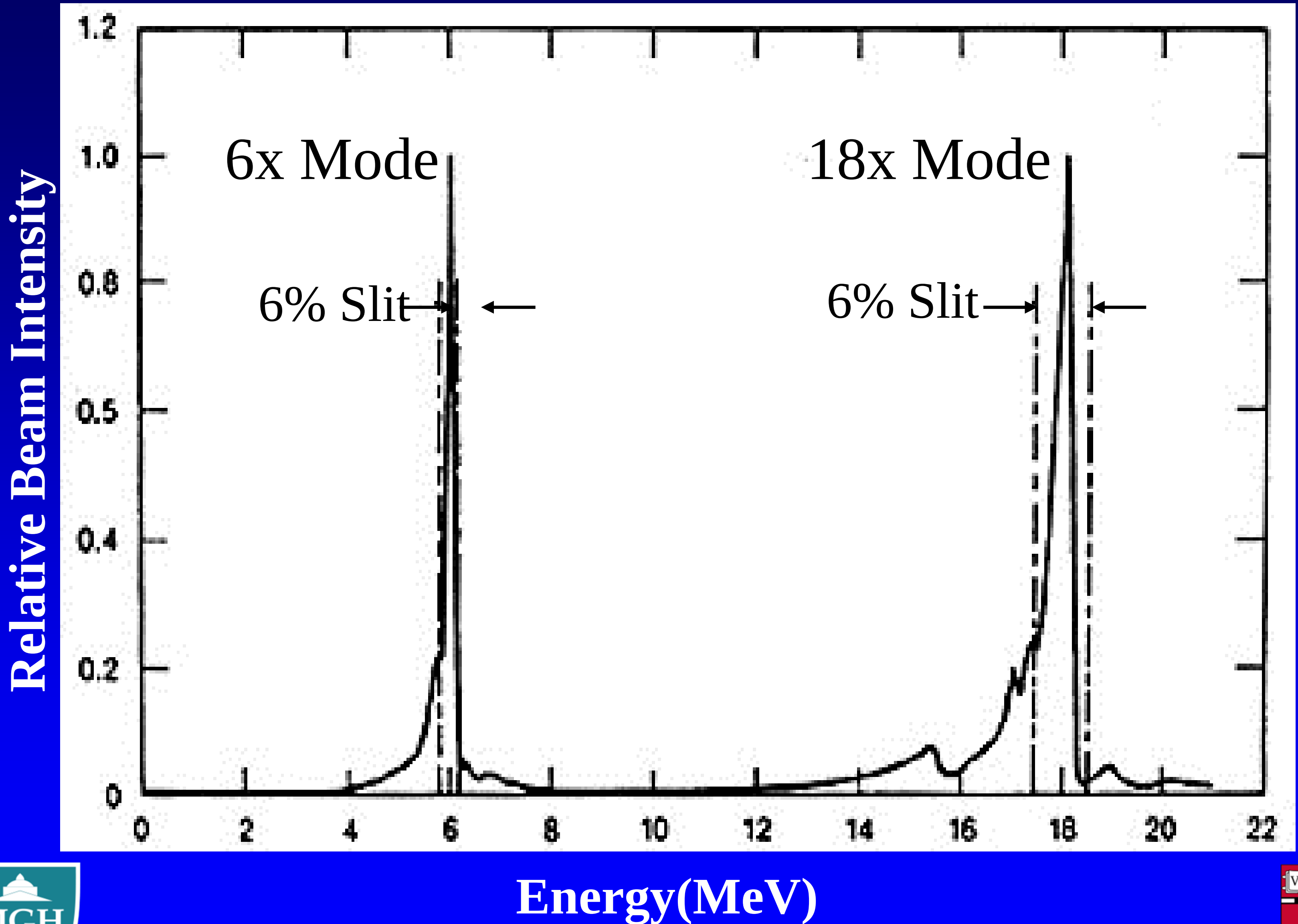
X-Ray Outputs with Energy Switch



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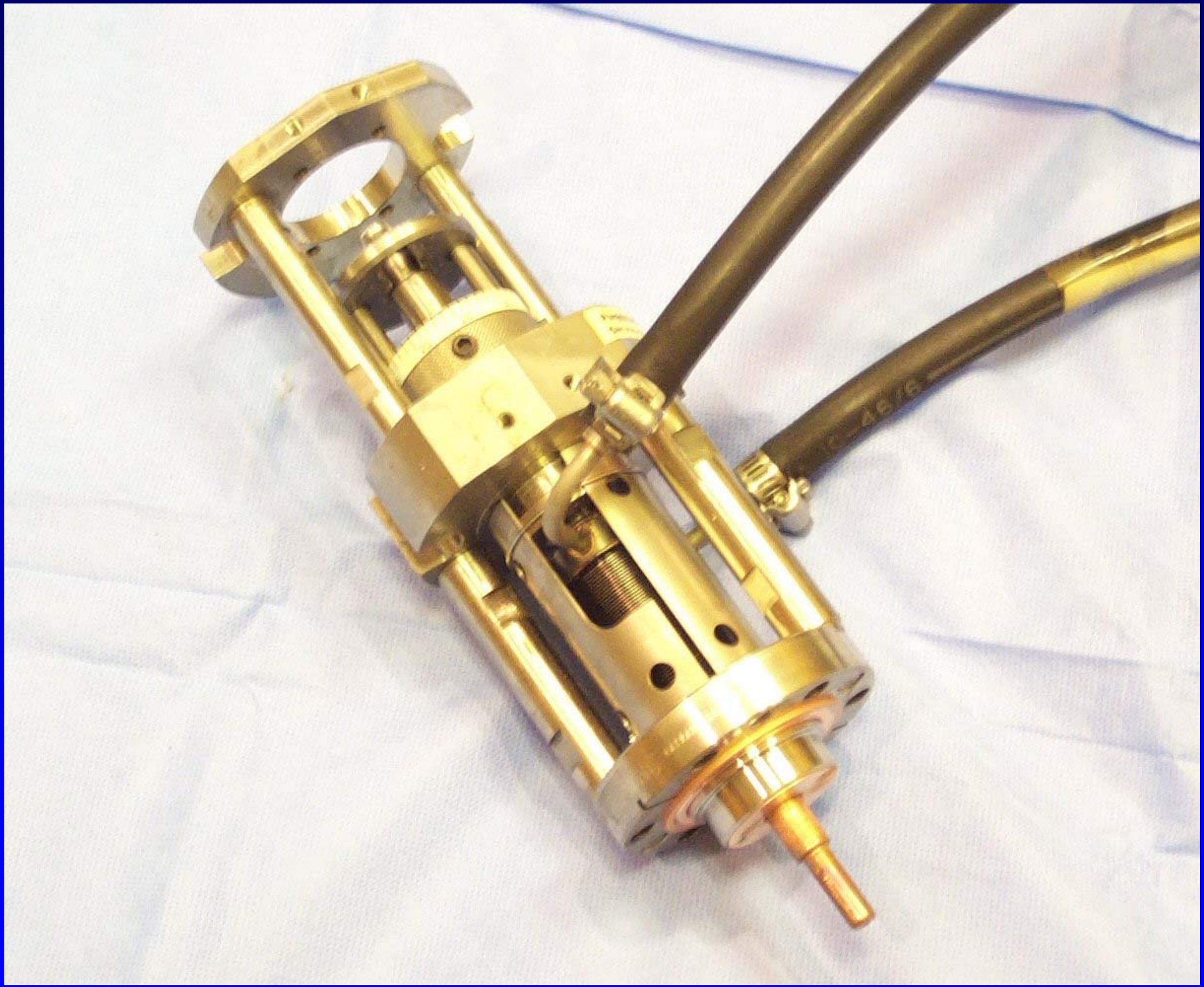
Energy Switch



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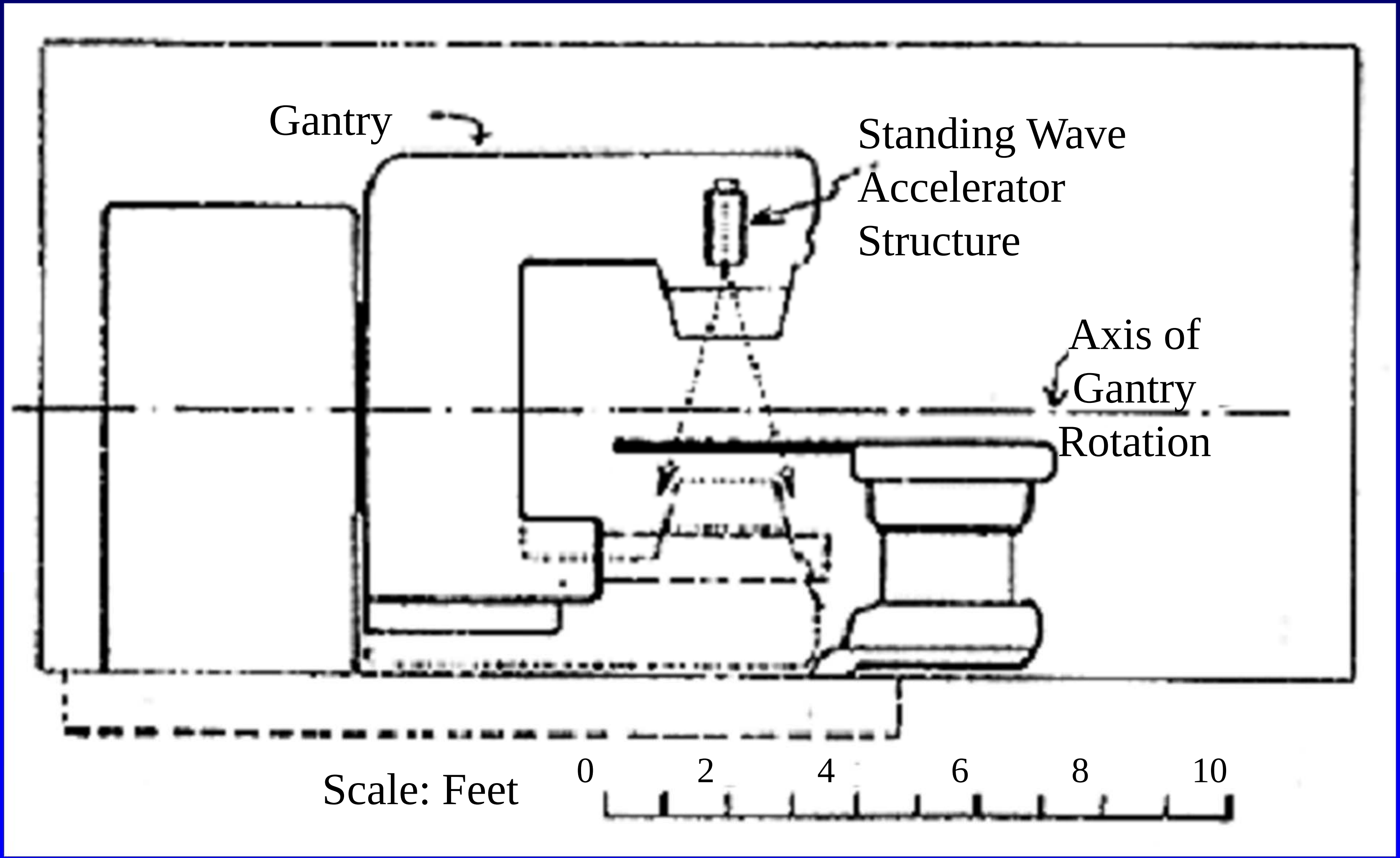
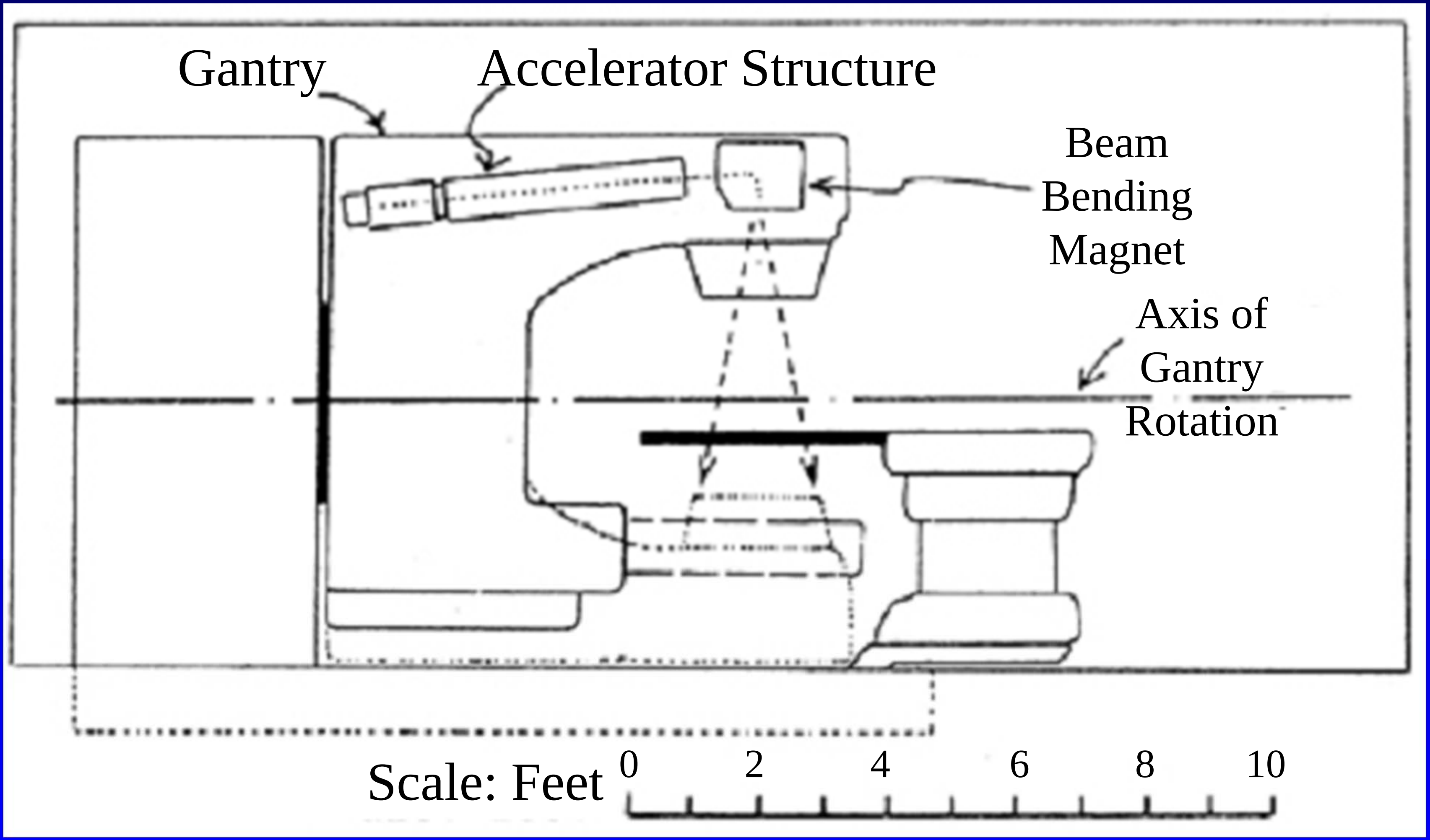
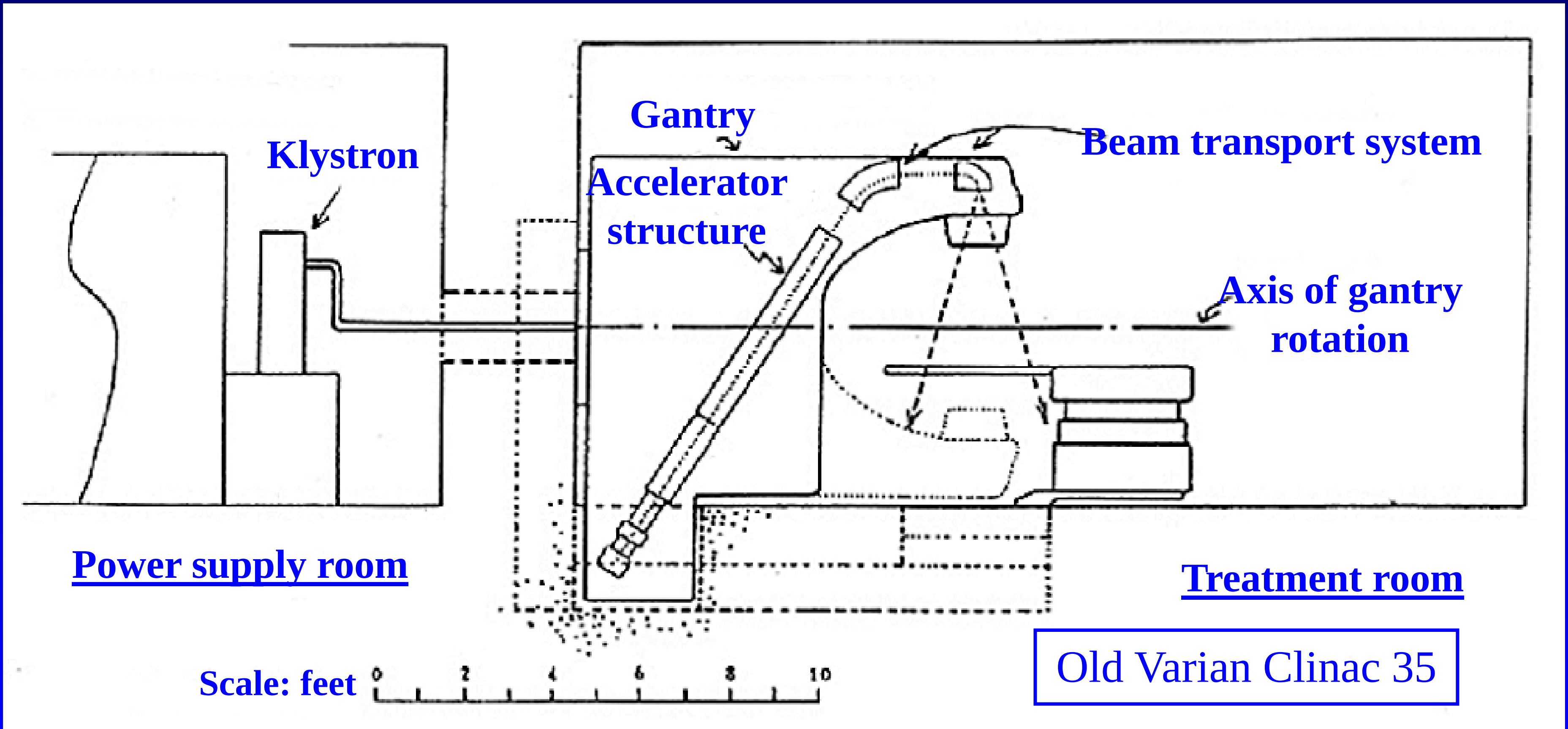
In-Line, No Magnet Linac



WG Parallel to Rotation Axis

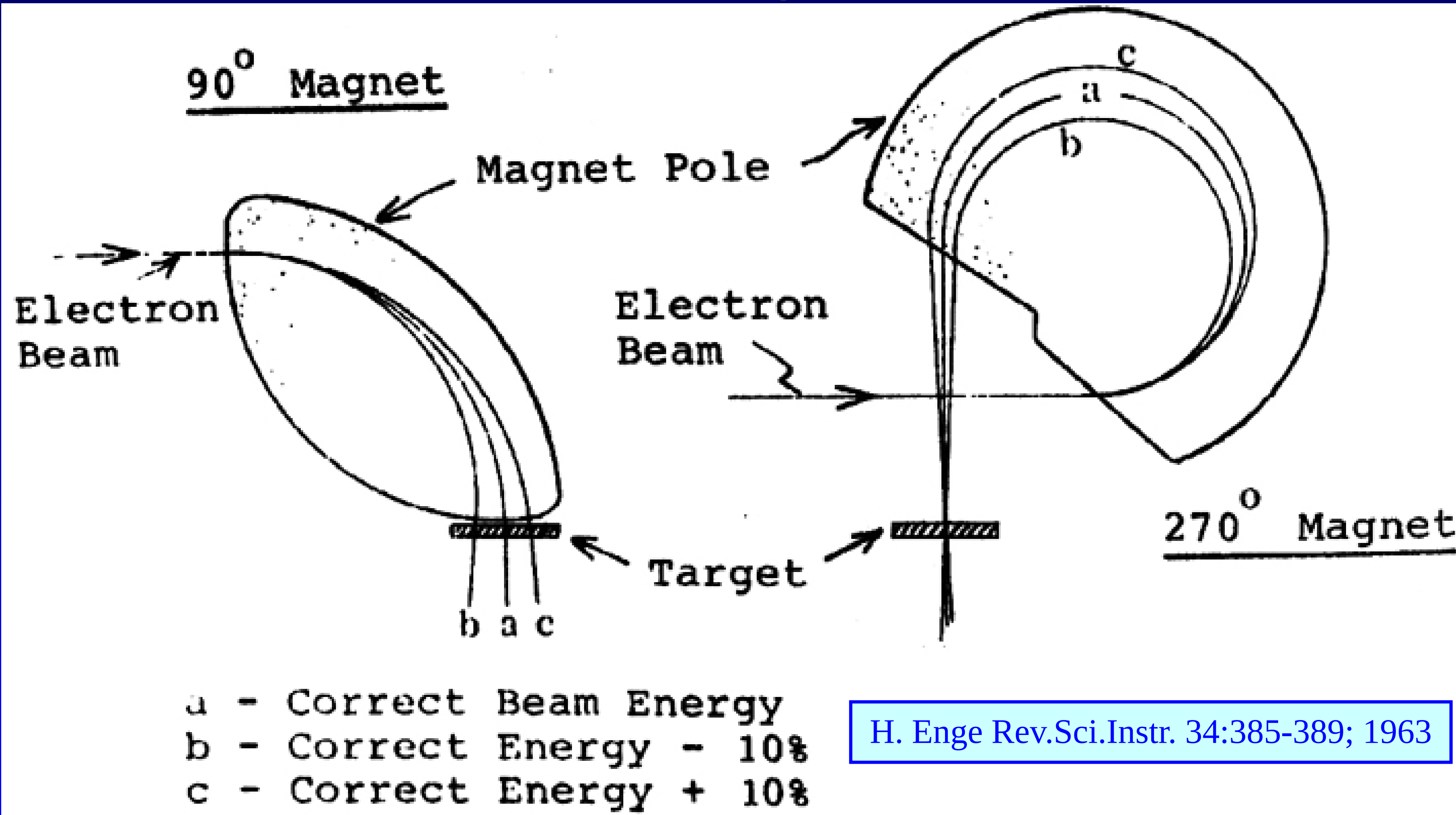


WG at Angle Relative to Rotation Axis



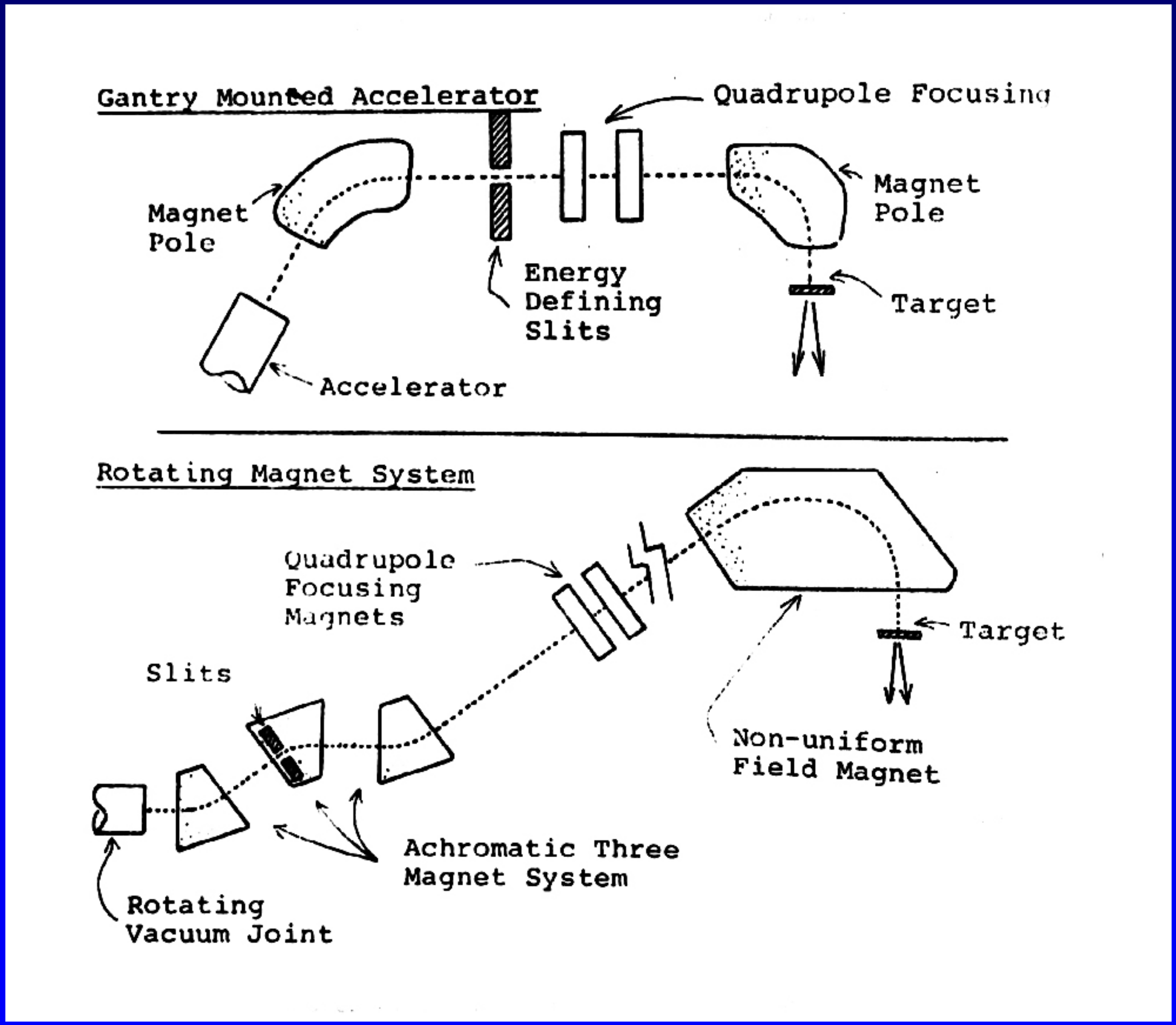
Note that Elekta machines use a travelling w/g without a pit for the gantry and a magnetron instead of a klystron

90° vs.270° Magnet Schemes

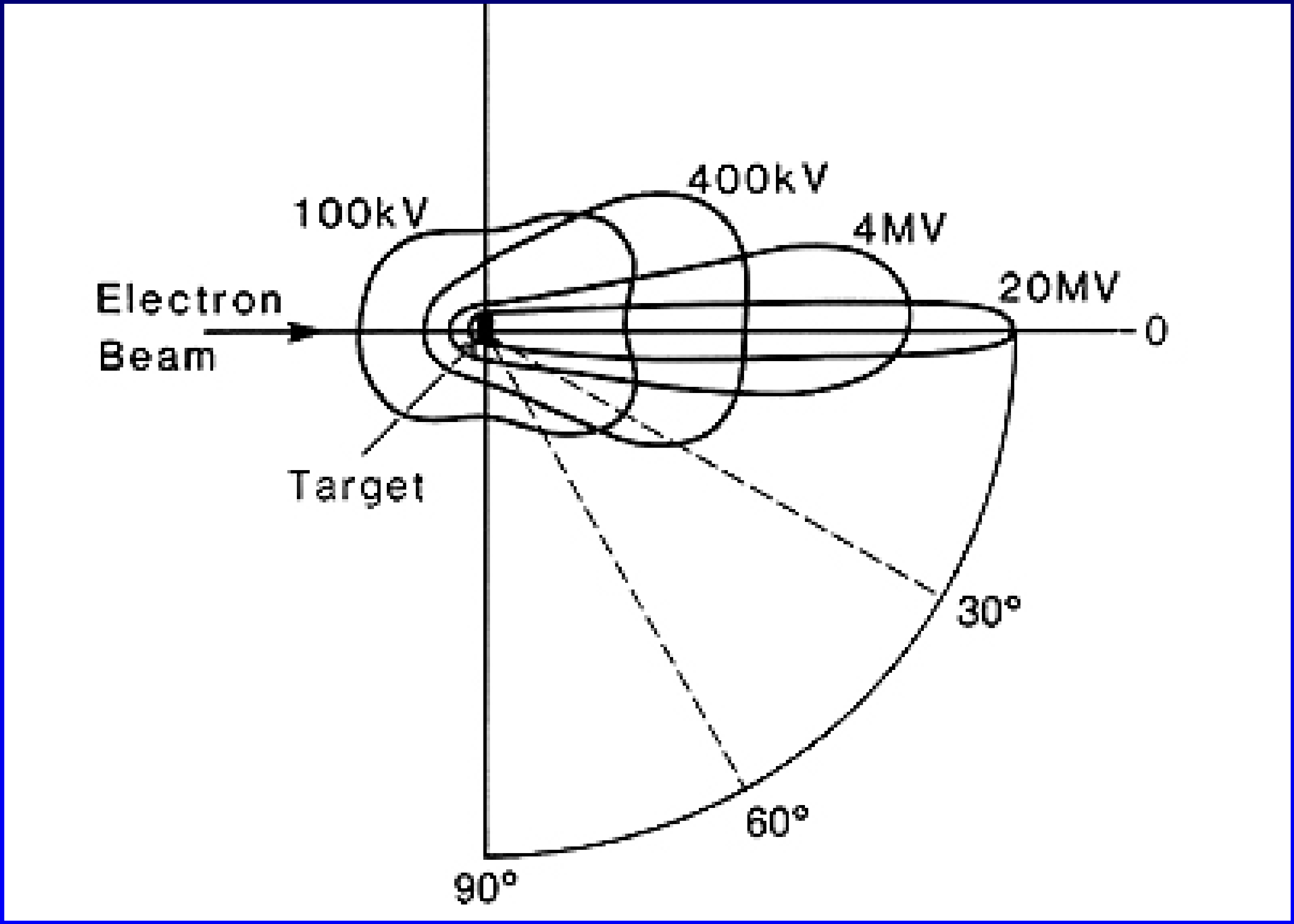


H. Enge Rev.Sci.Instr. 34:385-389; 1963

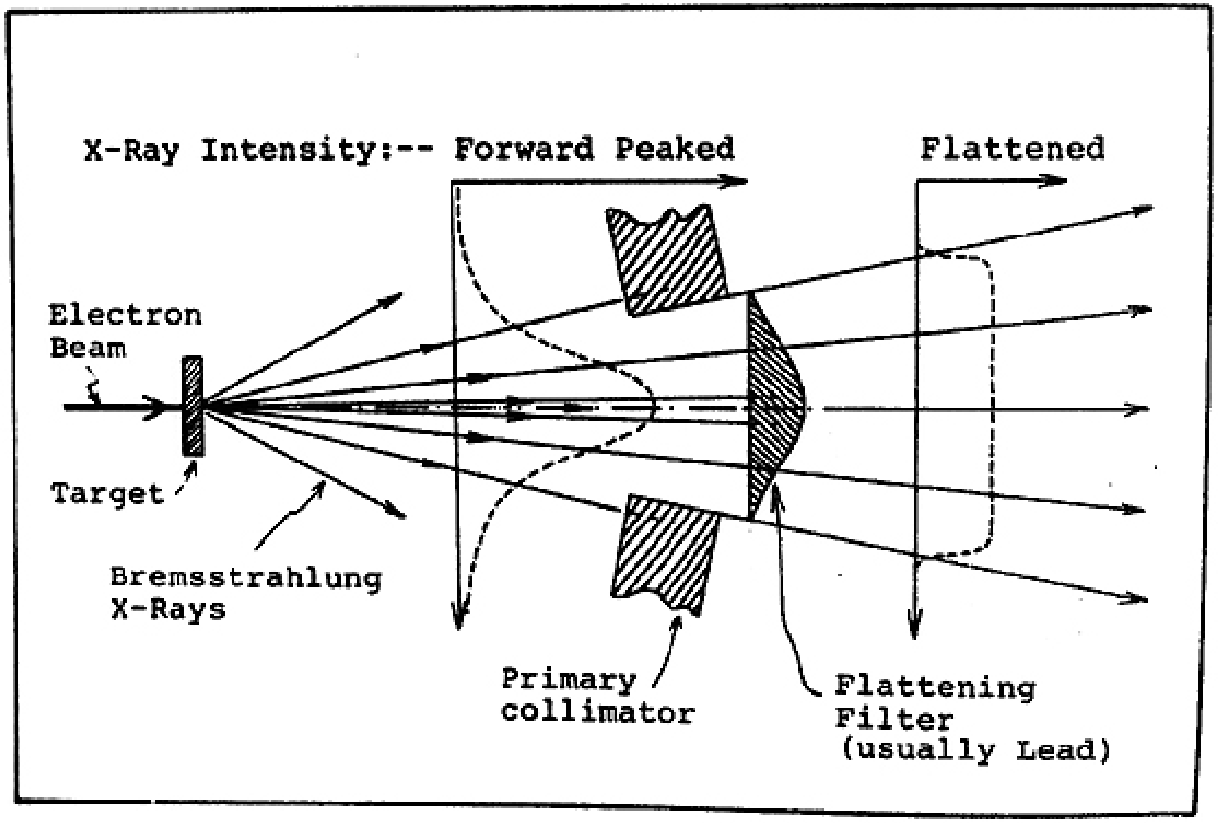
Alternative Magnet Schemes



Beam Envelope of X-Ray Production

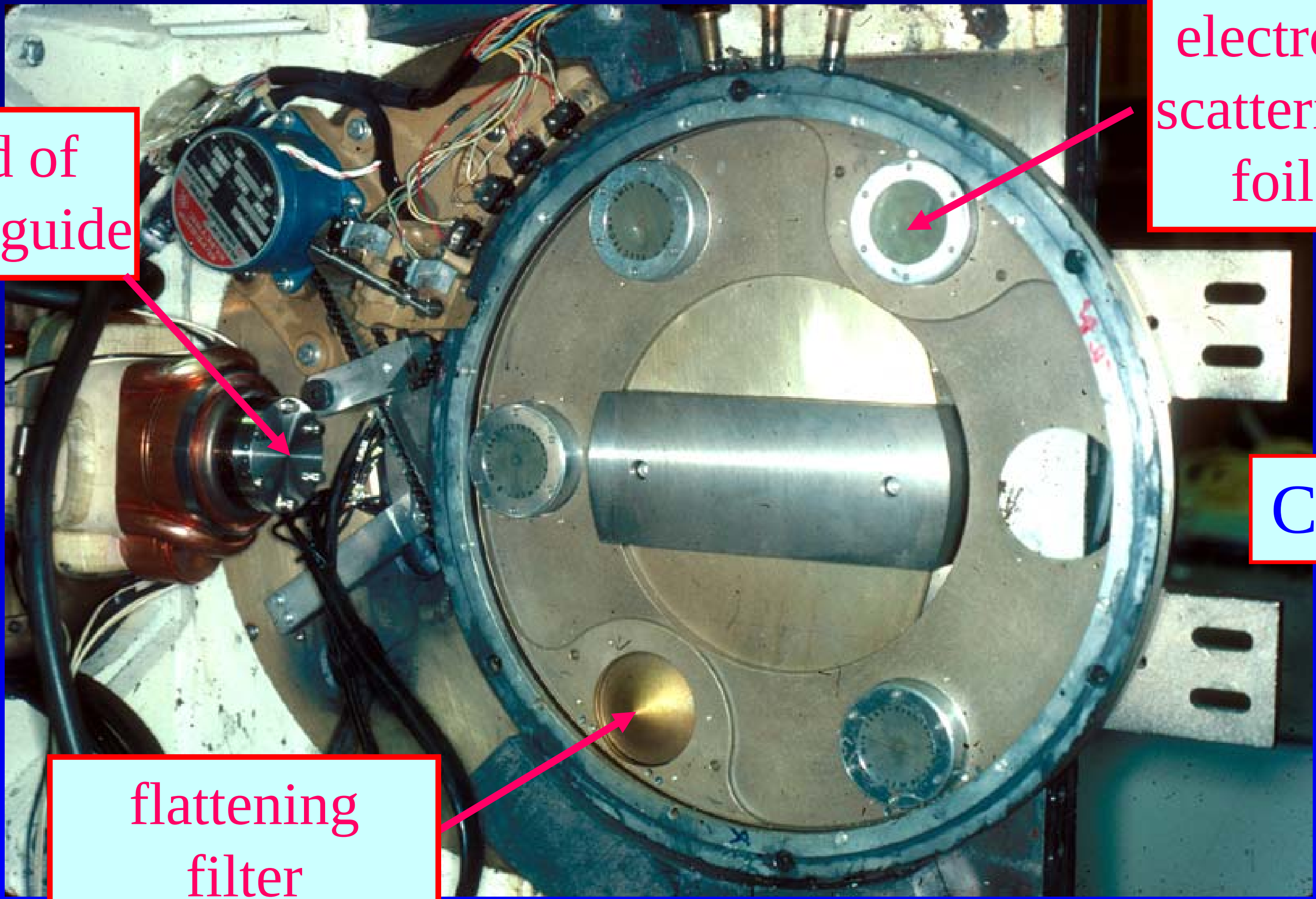


Principle of Flattening Filter



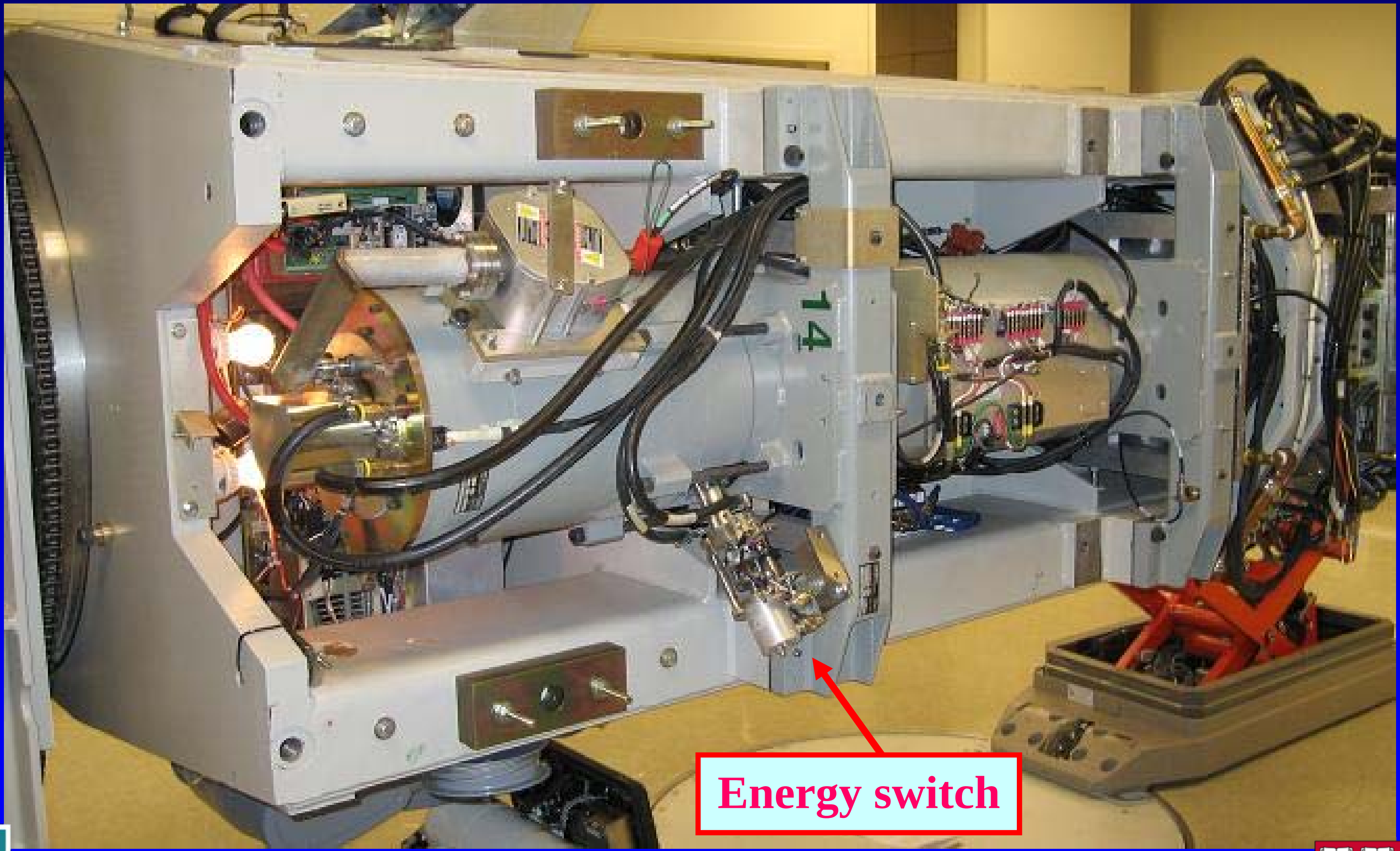
note that the flattening filter design is a compromise between flat fields at small and large field sizes – hence the horns at max. field size

Flattening Filter, Scattering Foil Carousel



Clinac 18

Top of Gantry (at 270°)



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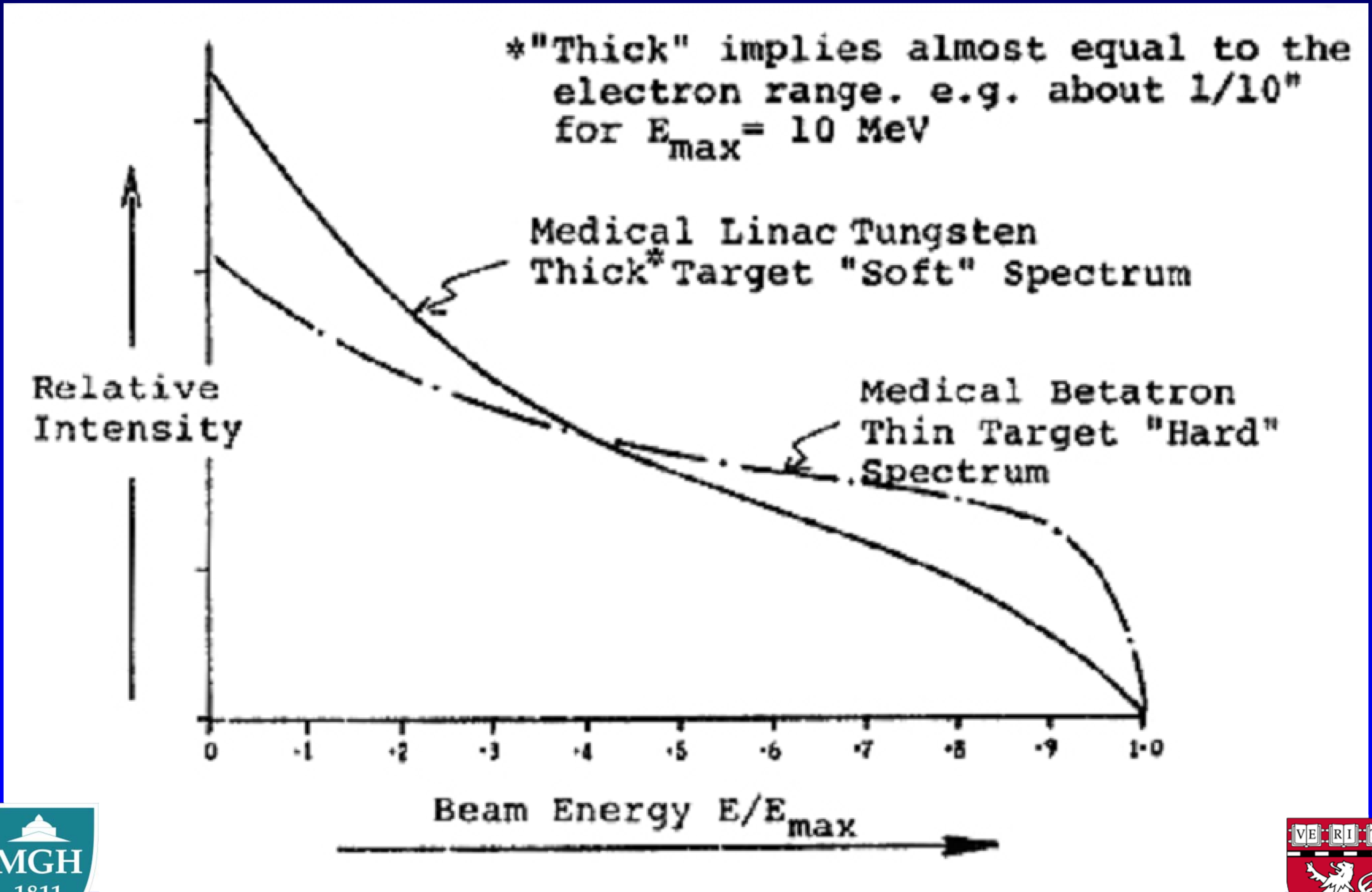
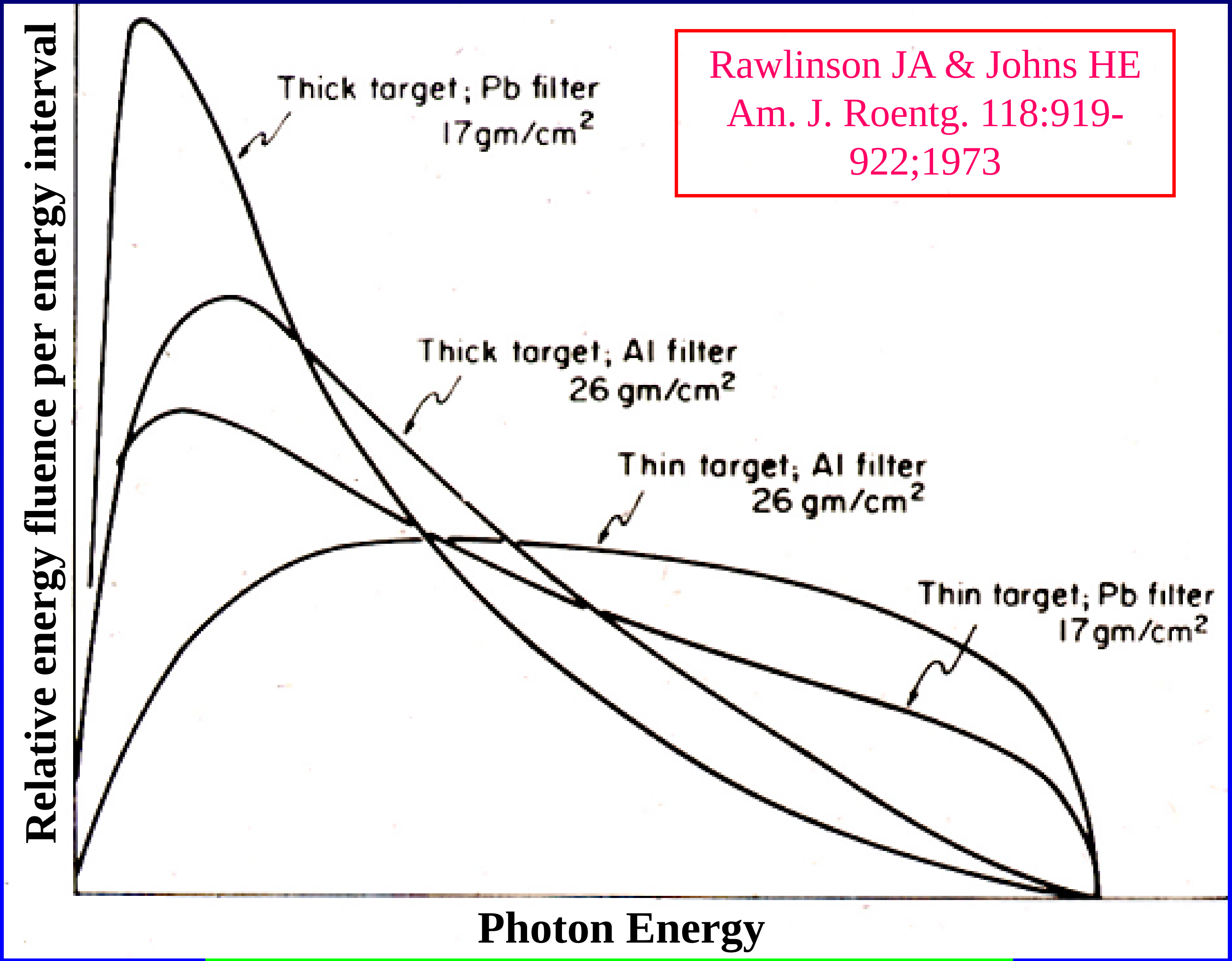
High Energy Linac With No Covers

Thin vs. Thick Target Spectrum

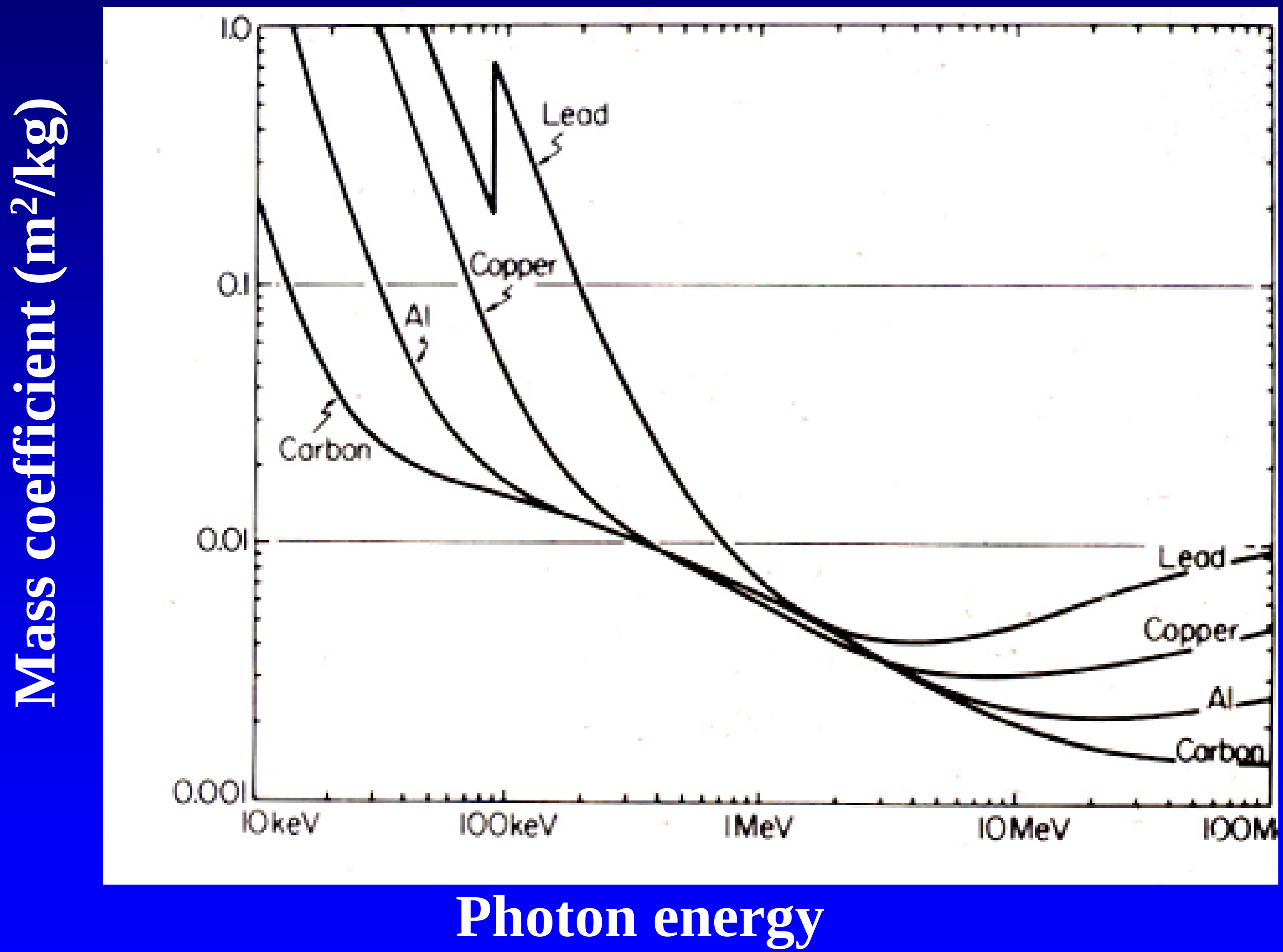


Expected Fluence Spectra for Various Target, Flattening Filter Combinations



Rawlinson JA & Johns HE
Am. J. Roentg. 118:919-922;1973

Total Attenuation Coefficient for Carbon, Aluminum, Copper and Lead



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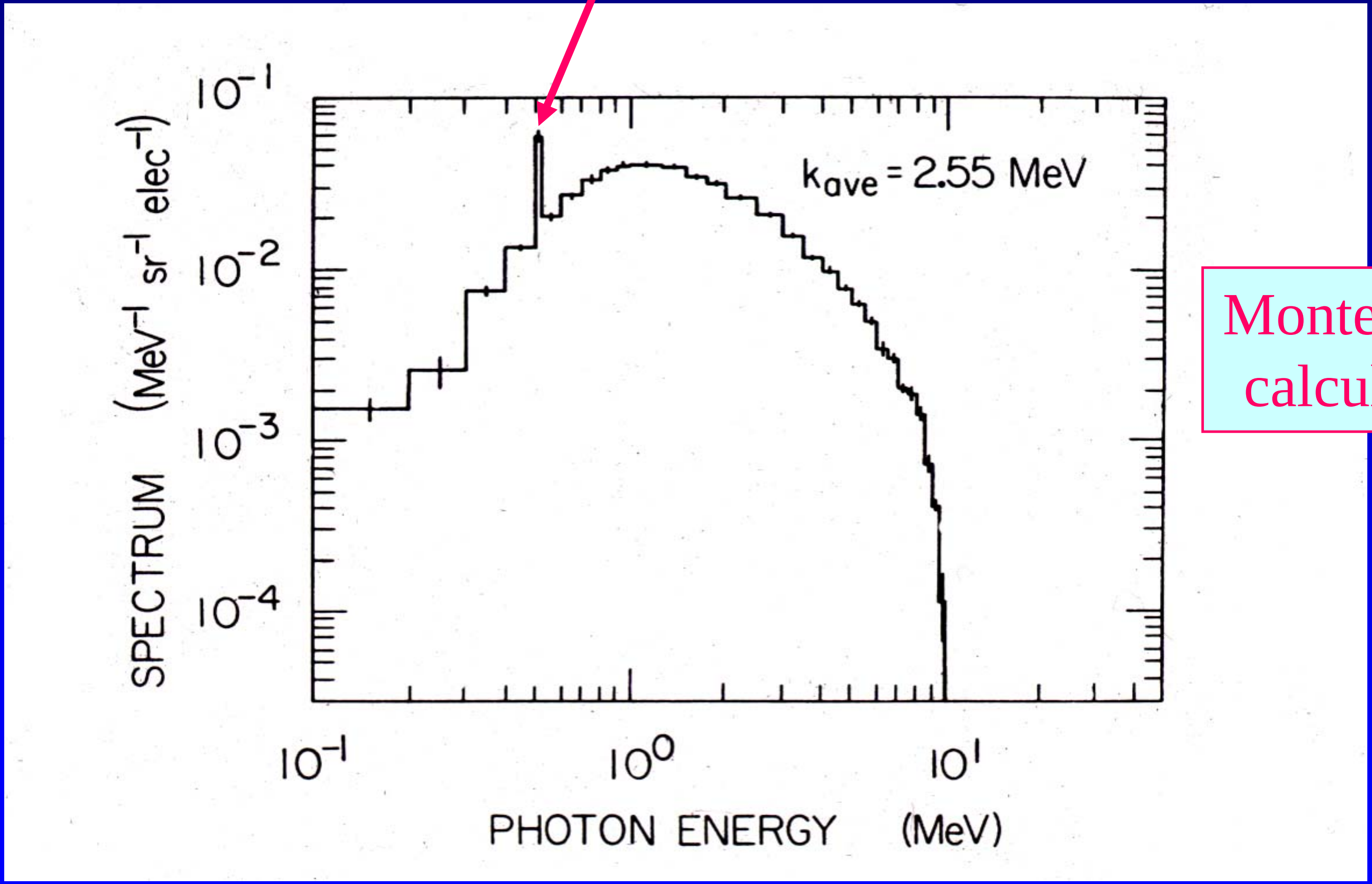
10 MeV Primary Spectrum (0° to 15°)

annihilation peak

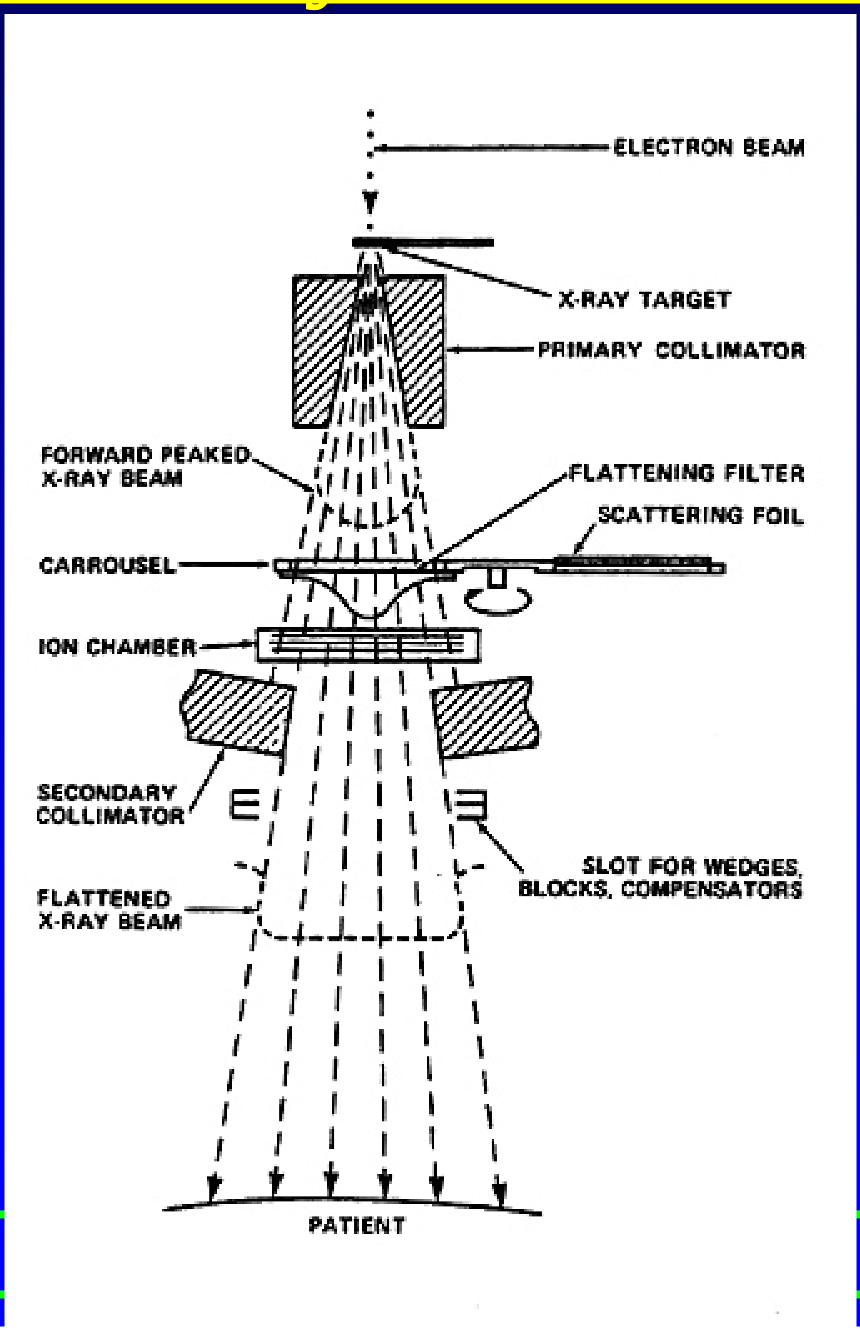


Monte Carlo calculation

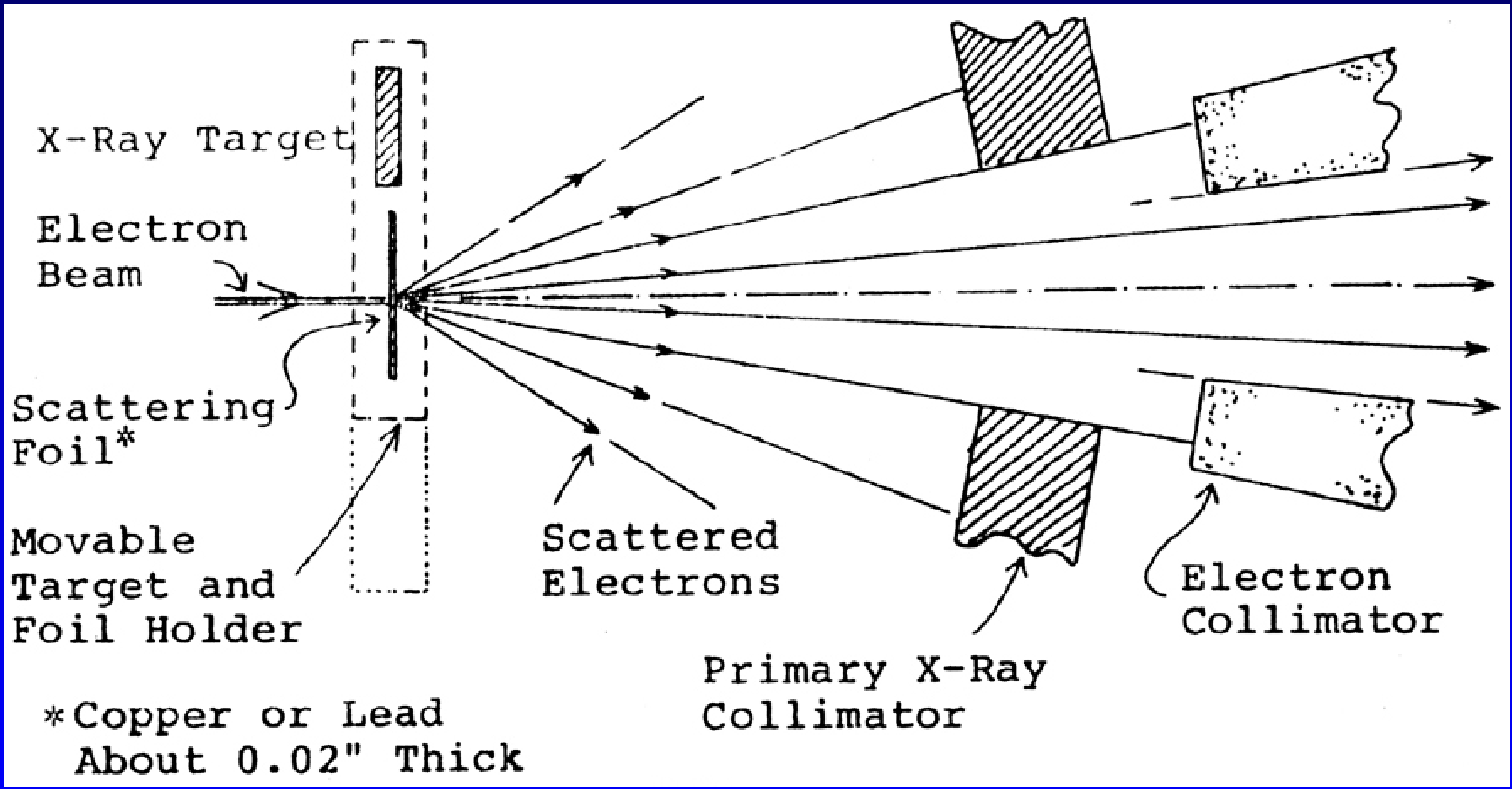
Average Photon Energy (MeV) of Primary Radiation for Various Incident Electron Energies

Angle (degrees)	Electron Kinetic Energy		
	6 MeV	10 MeV	25 MeV
0-15	1.76	2.55	4.75

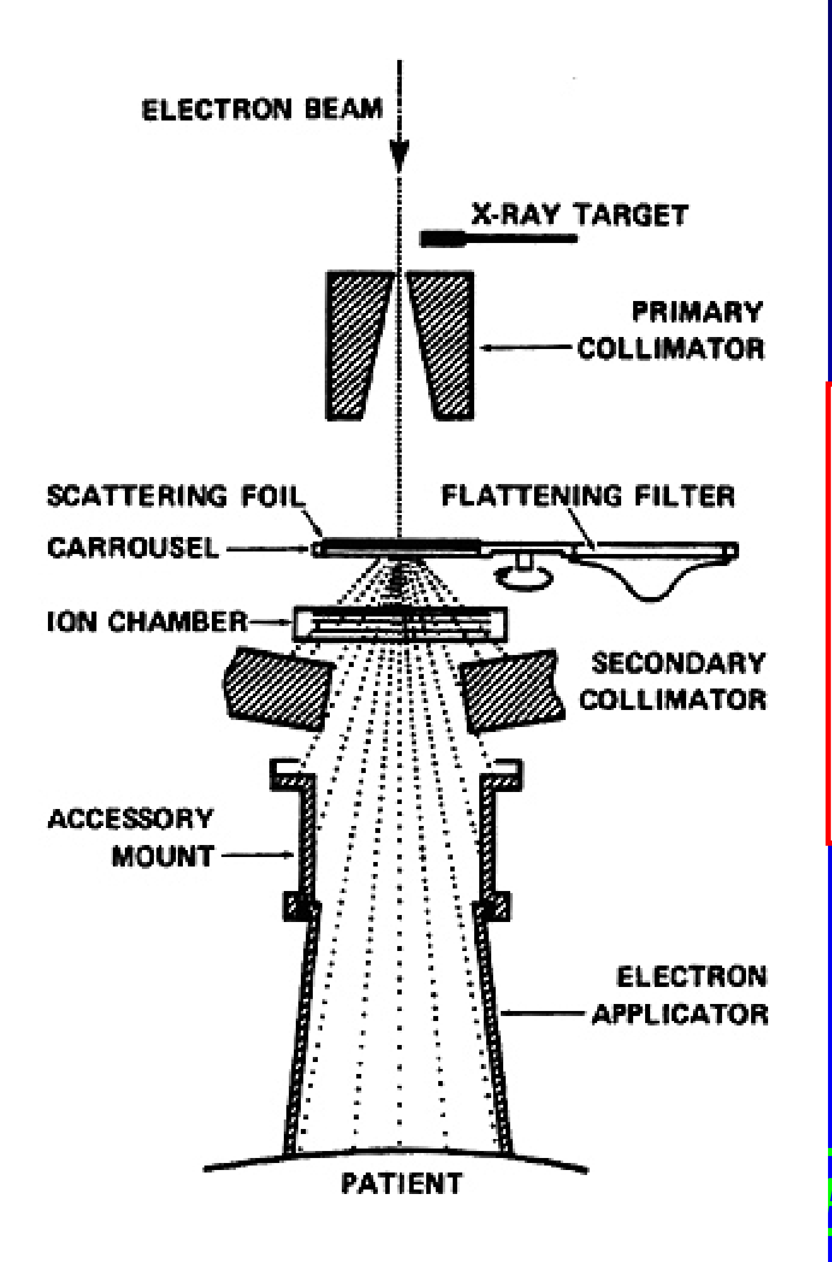
Clinical X-Ray Beam Production



Scattering Principle for Electron Beams

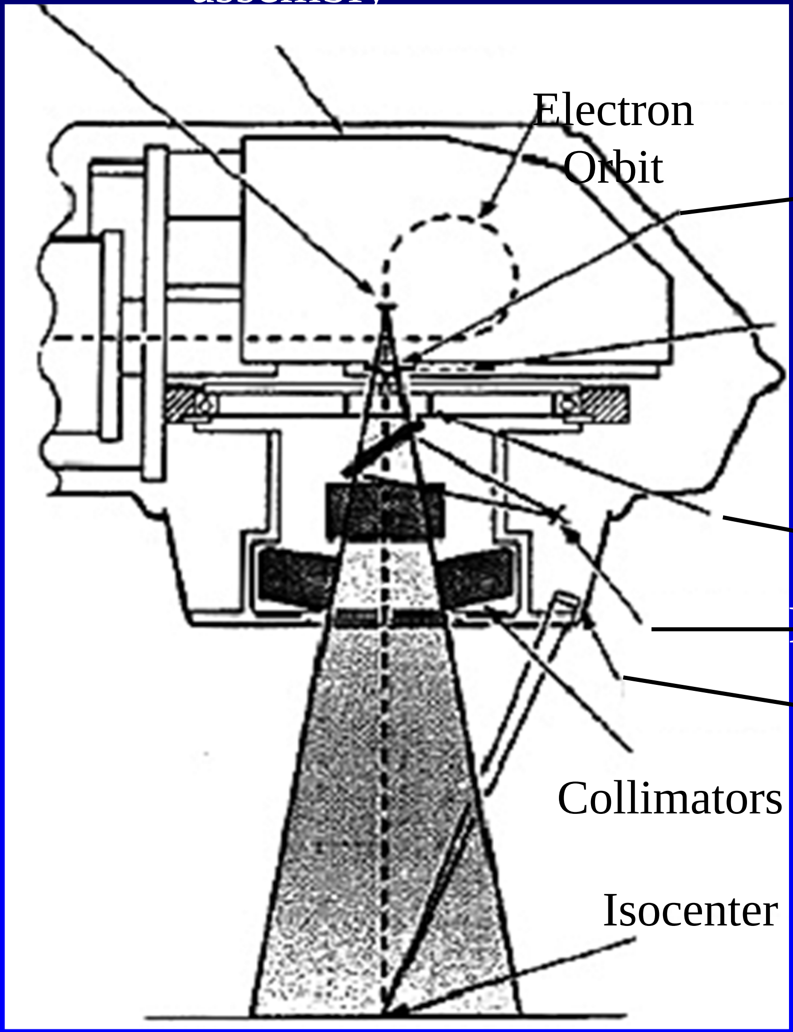


Clinical Electron Beam Production



Current e-applicators have a space (~5 cm) between the bottom of the applicator and 100 cm SSD for patient setup

Overall Layout of Linac Head (Varian)

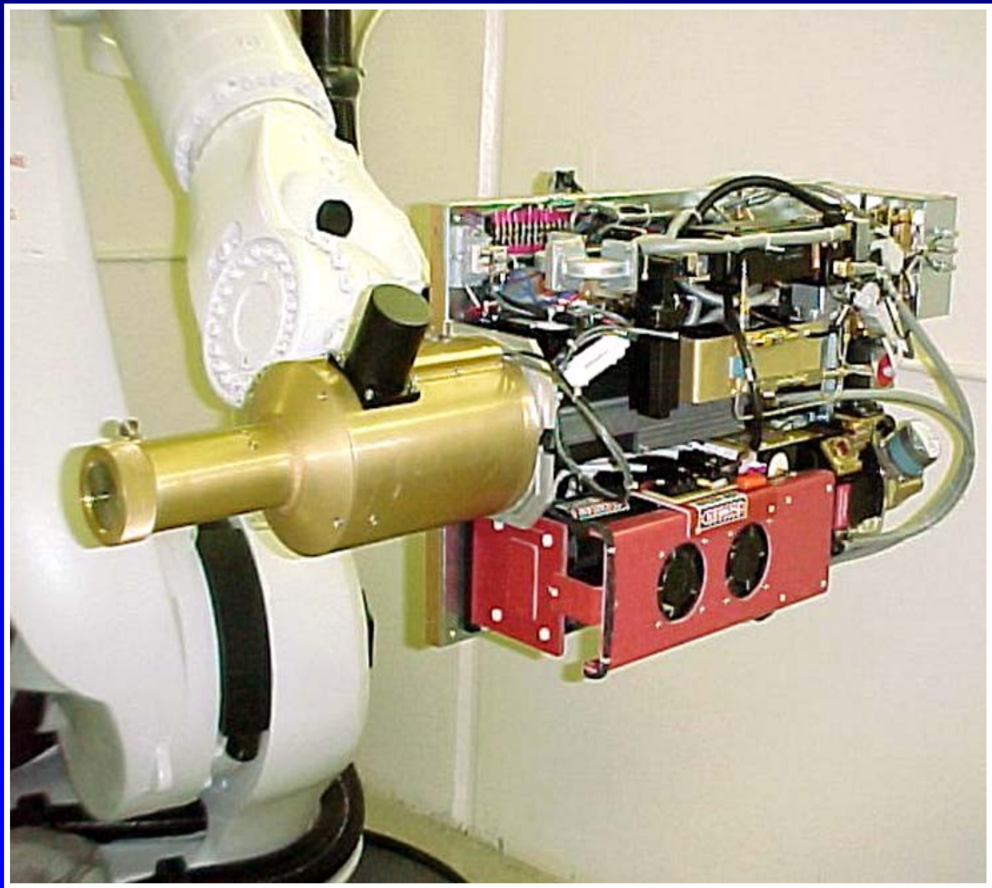


Cyberknife

(slides courtesy of Xing-Qi Lu,
BID Medical Center)

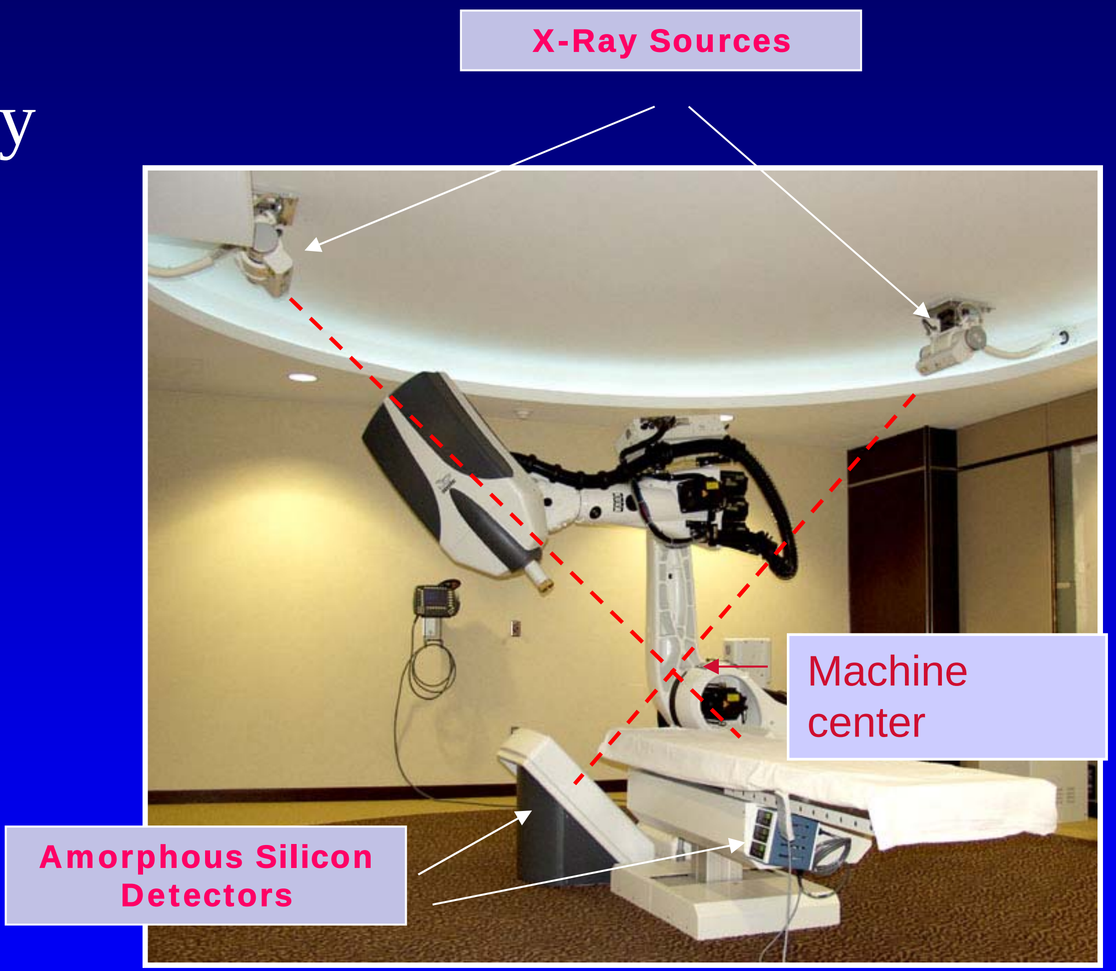
Linear Accelerator

- 330 lbs. (150 kg)
- 6 MV X-band
  - 9.3 GHz microwaves
- 400/600 MU/min
- 12 circular collimators
  - 5 to 60 mm



Imaging System

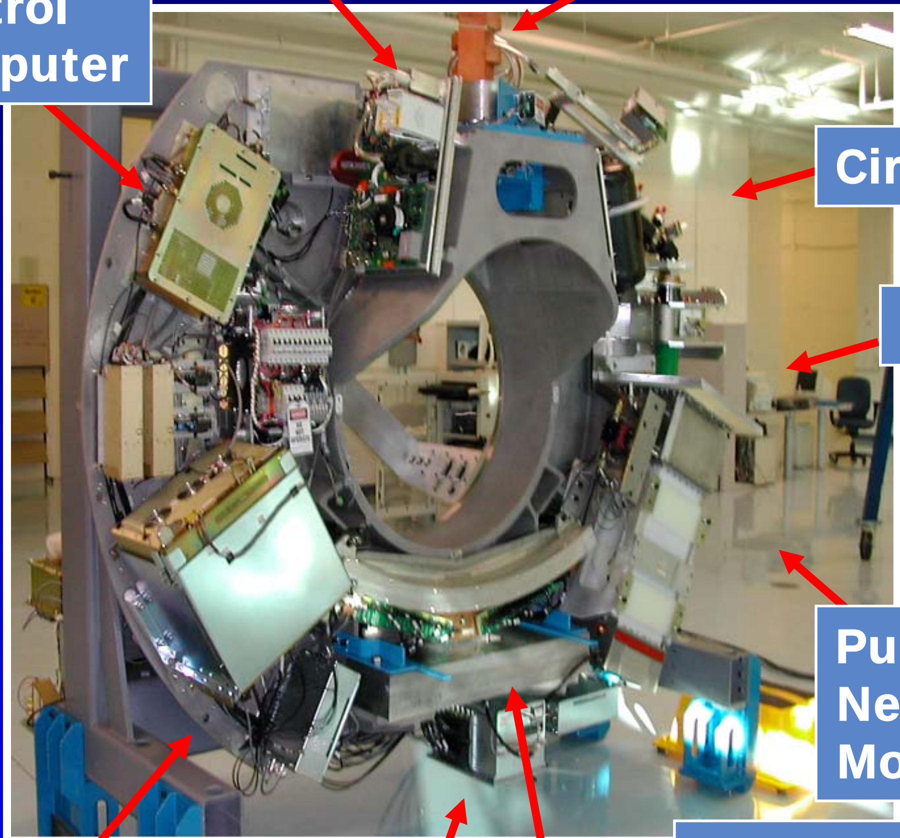
- 2 diagnostic X-Ray sources
- 2 image detectors (cameras)
- Patient imaged at 45° orthogonal angles
- Live images



The Mobetron IORT Machine is also an X-Band Machine

Tomotherapy: Under the Covers

Note: VERO system is similar to this but can adjust MLC for target motion



Slide Courtesy of Tomotherapy, Inc.

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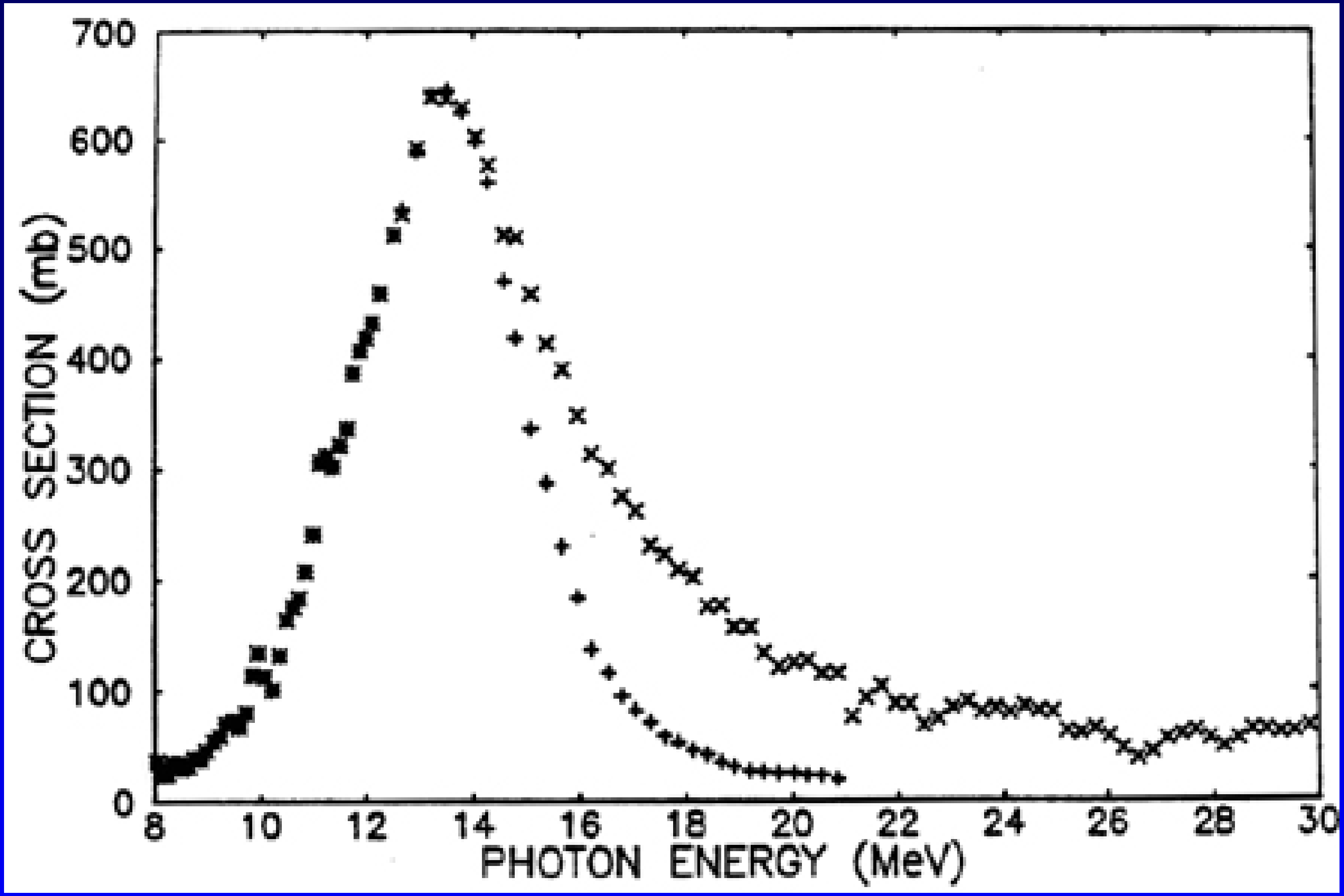
Photoneutron Production Cross-Sections



The (γ,xn) and (γ,In) cross sections for ^xx^Pb. The (γ,xn) and (γ,In) cross Sections are represented by crosses and plus signs, respectively. Above 14.9 MeV the (γ,In) cross section includes an unknown component from the (γ,pn) reactions (Veyssiere et al, 1970).

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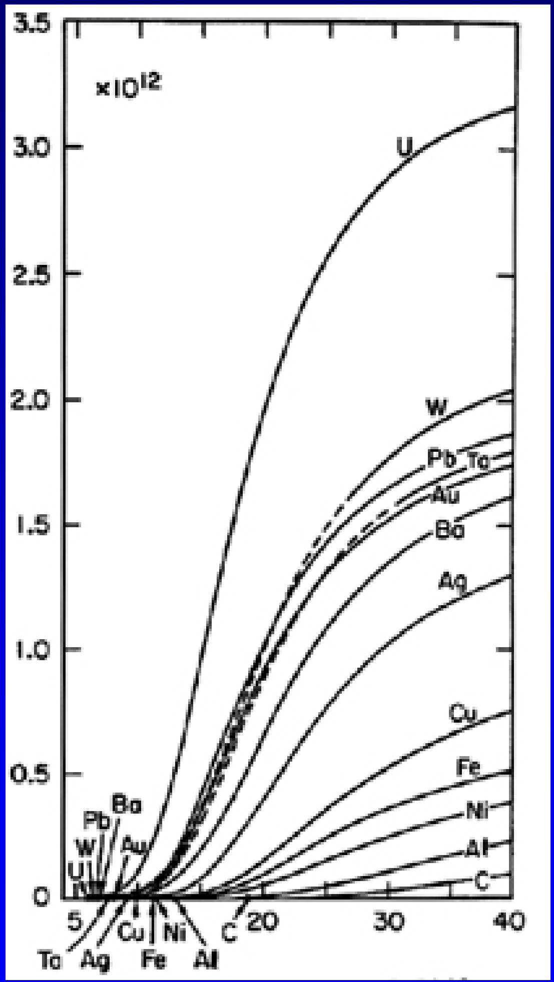
Neutron Yield vs Energy, Z

Y (neutrons sec^{-1} kW^{-1})

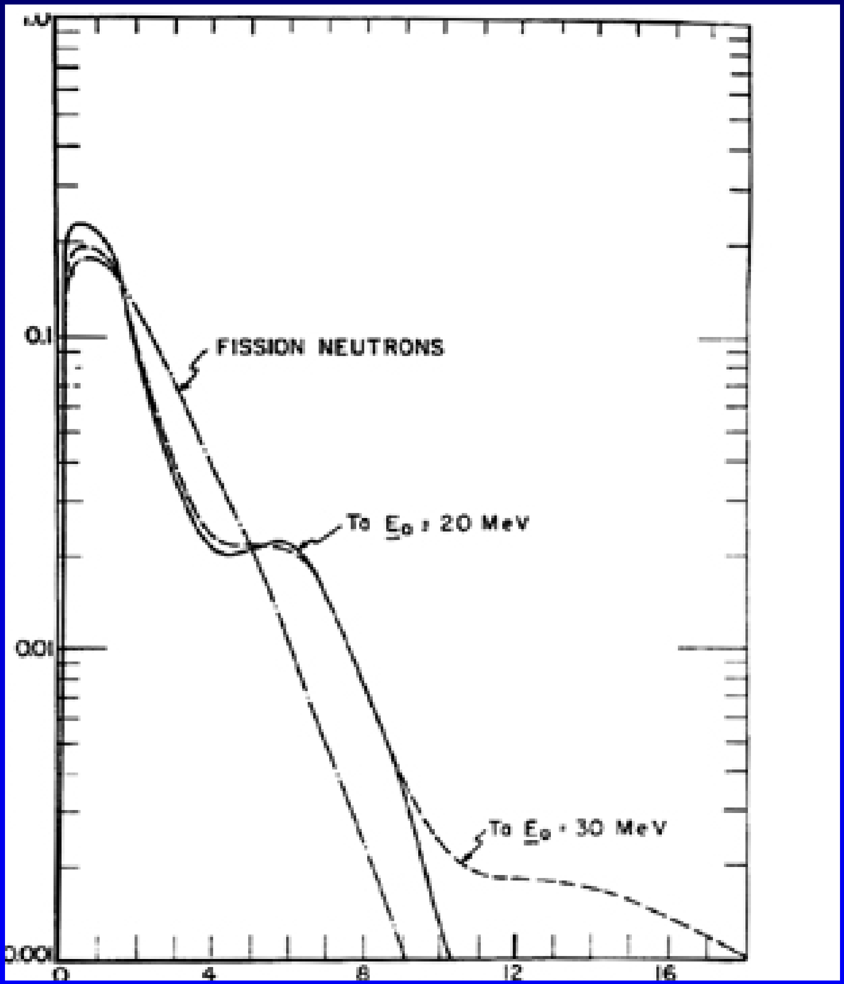


Electron Energy E_0 (MeV)

Neutron yields from semi-infinite targets of various materials per unit incident electron-beam power as a function of incident electron energy E_0 (Swanson, 1979).

Photoneutron Energy Spectra

Relative number of neutrons per ½ MeV



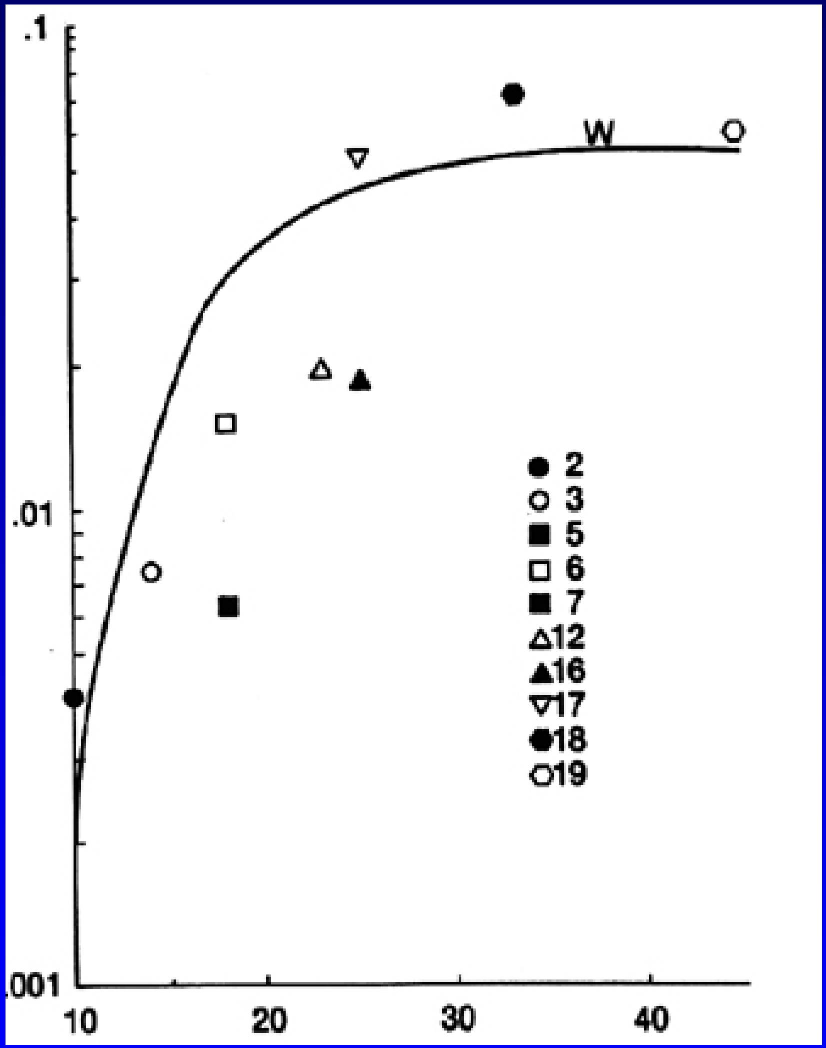
Neutron Energy, E_n (MeV)

Photoneutron spectra for tantalum with peak bremsstrahlung energies of 20 and 30 MeV. A fission neutron spectrum is shown for comparison (NCRP, 1964).

MGH 1811

VE RI TAS

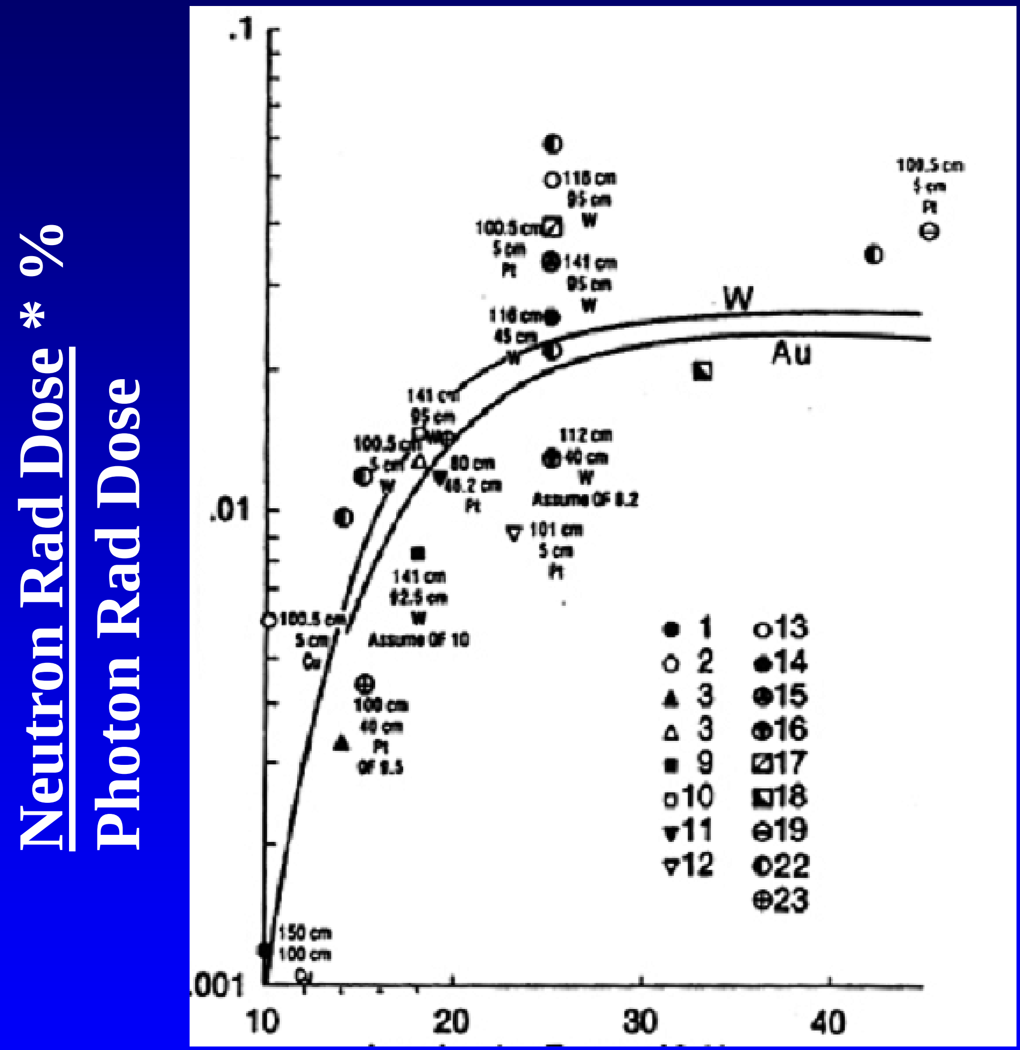
Neutron Leakage: In-Beam



Neutron Rad Dose * %
Photon Rad Dose

Accelerator Energy (MeV)

Neutron Leakage: Out-of-Beam



Accelerator Energy (MeV)

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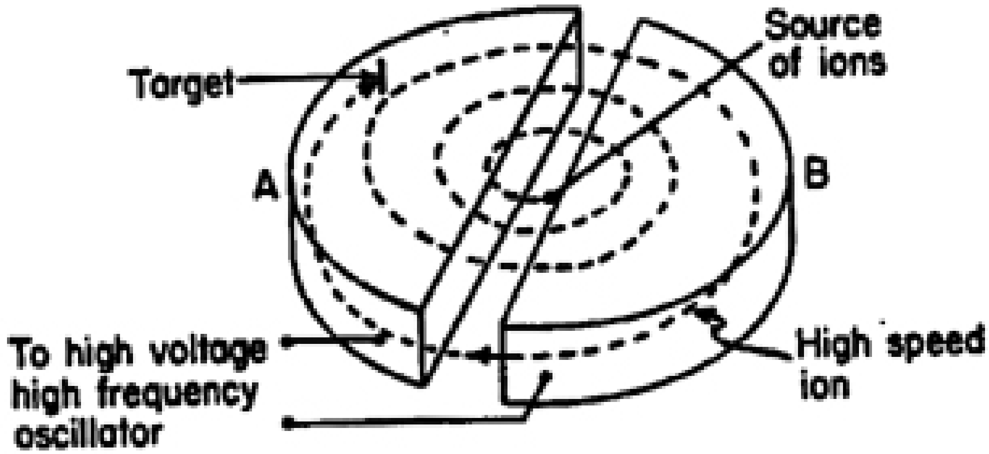
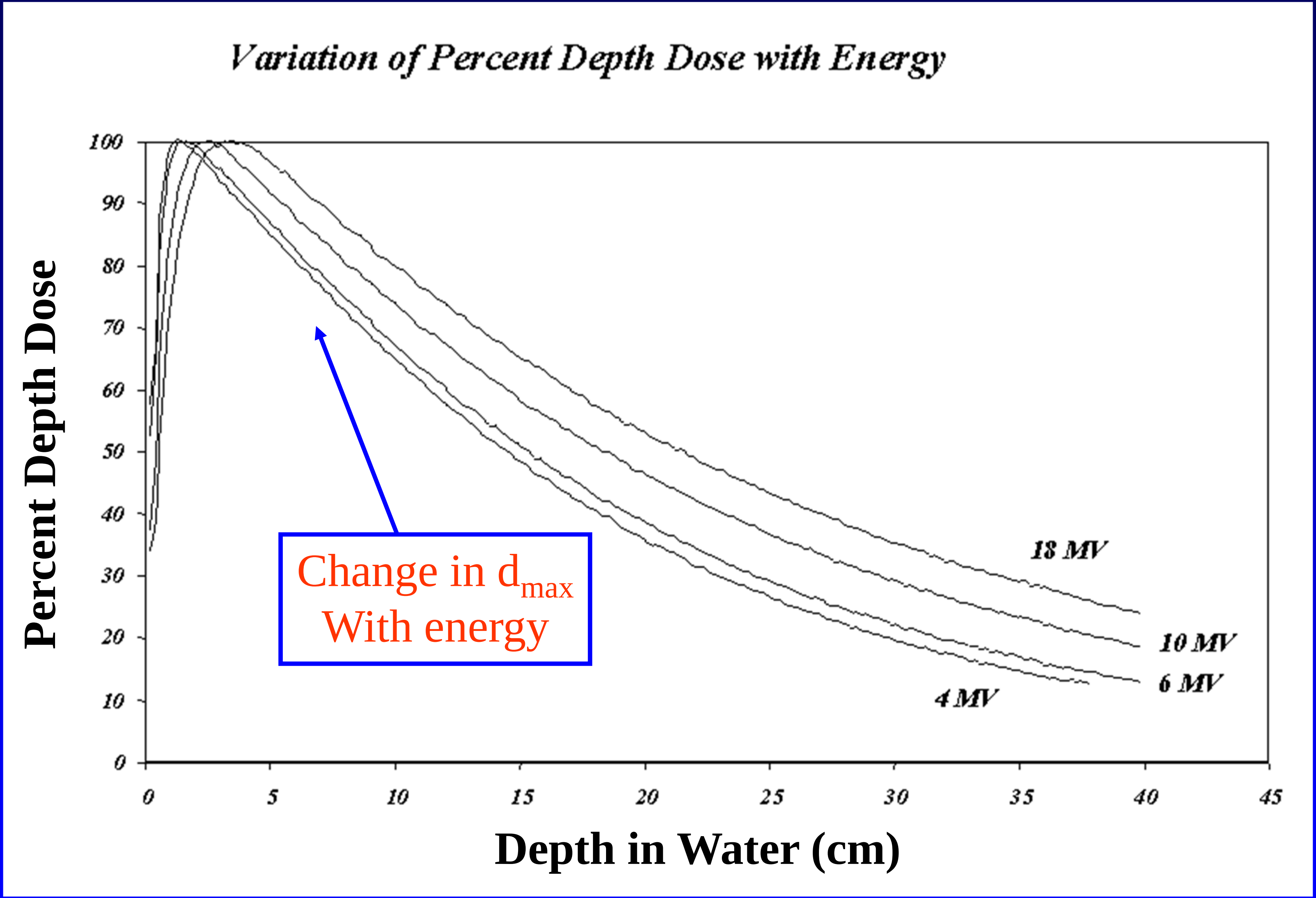
What to check after changing a ……

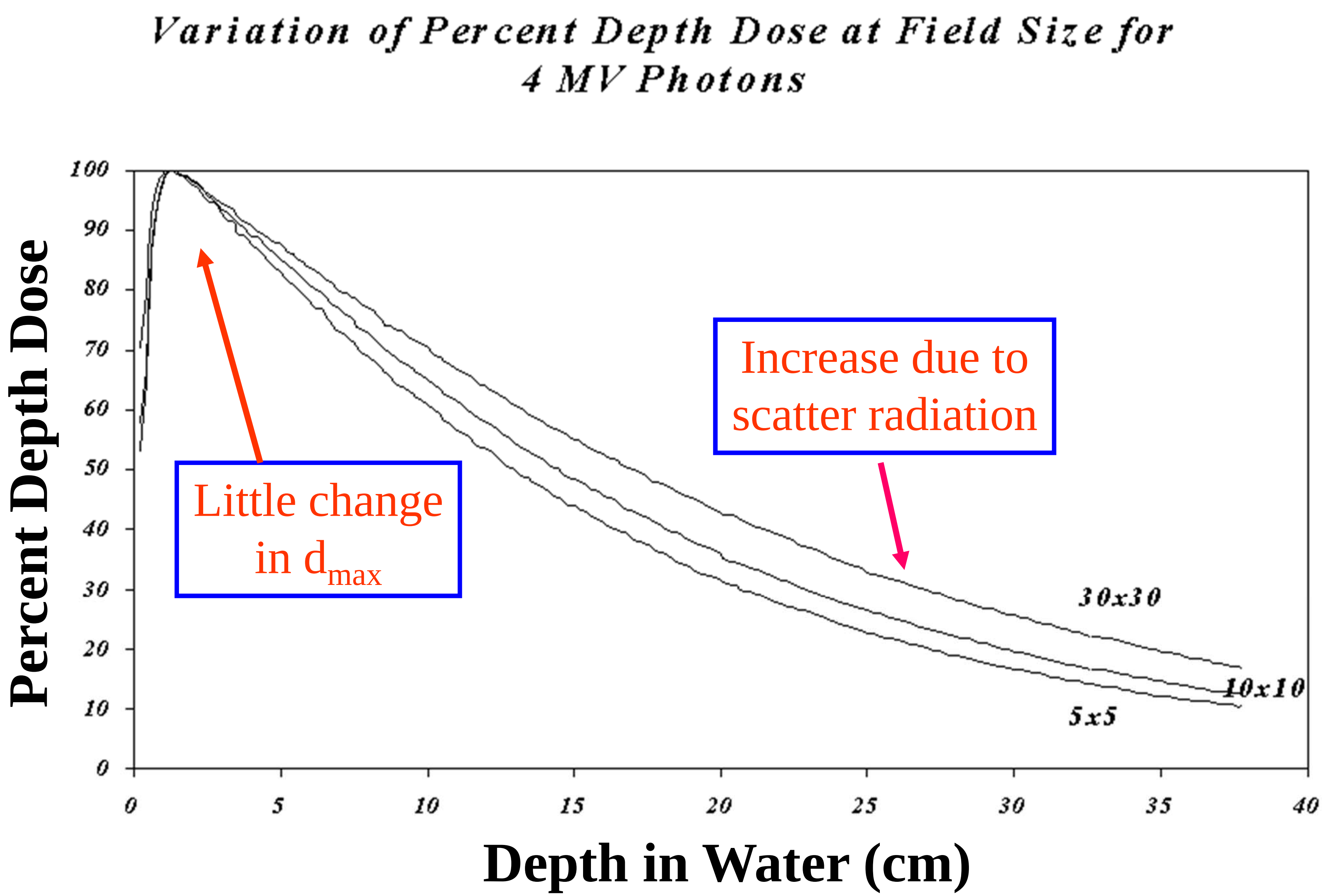
Machine	Component	Energy	PDD	Profiles	Dose calibration
In-line	Magnetron	X		X	X
	Ion chamber			X	X
	Tgt/gun/guide	X	X	X	X
With magnet	Klystron/magnetron	X			X
	Gun	X			X
	Ion chamber			X	X
	Foil/flattening filter		X	X	X
	Guide	X	X	X	X
	Bending magnet	X	X	X	X

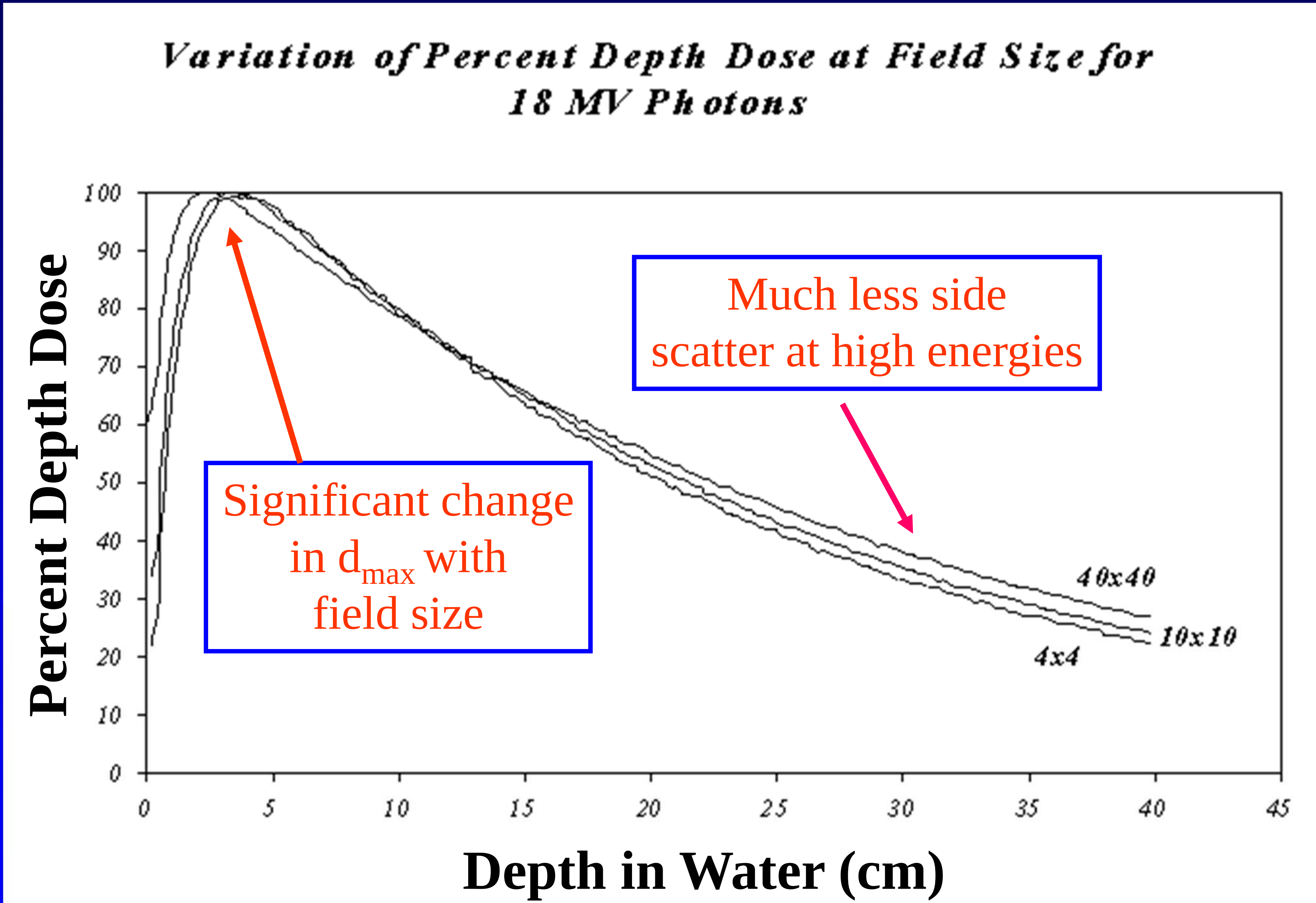
Cyclotron



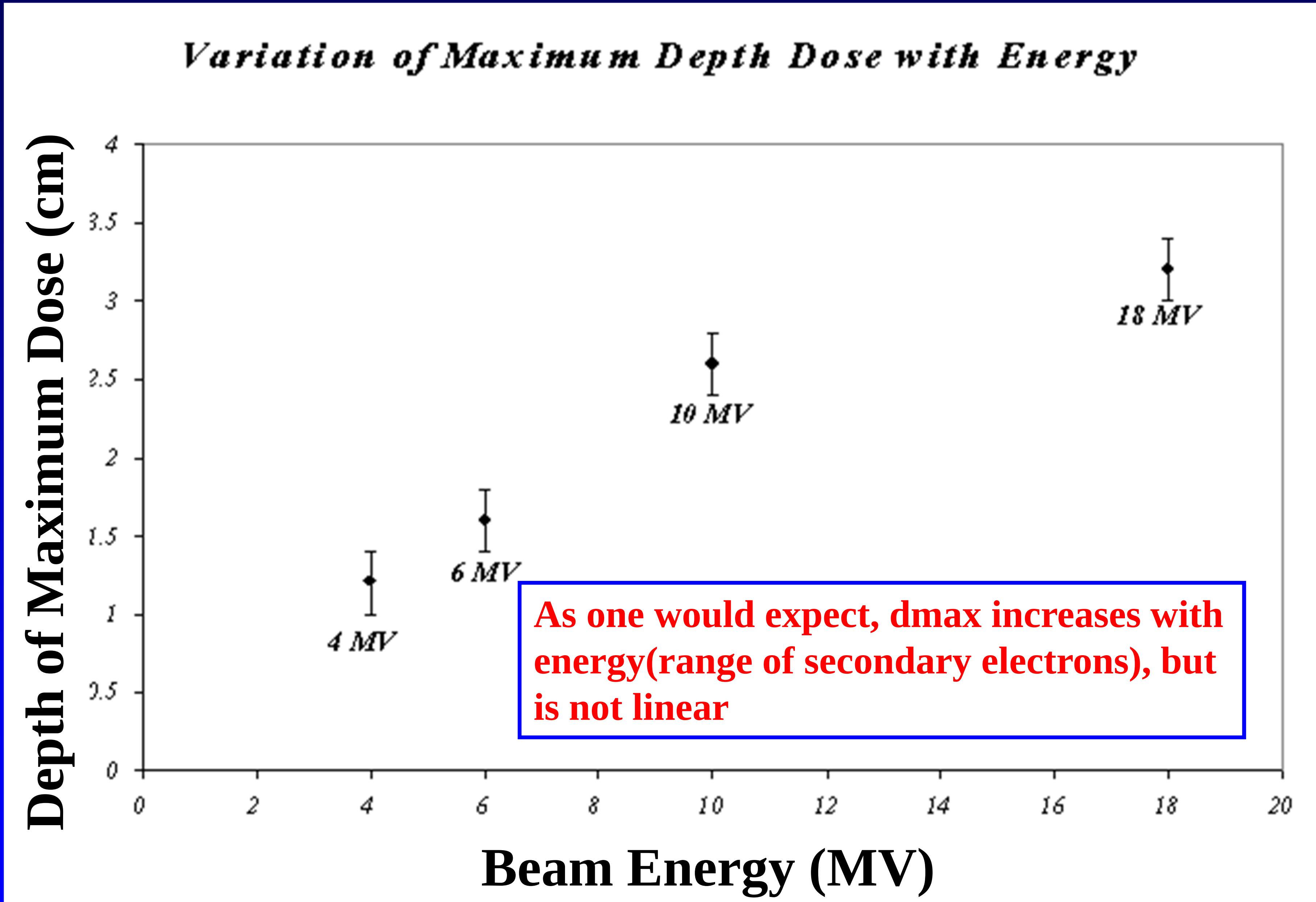
- particles travel in circular orbit, constrained by magnetic field.
- particles are accelerated by RF field applied between two D's between which the particles pass
- Revolution time, t, = pM/(H * e), independent of velocity or radius.
- Max energy limited by mass increase of particle (22 MeV for d). Higher energies can be achieved by modulating the frequency of the RF system. Such a machine is called a synchro-cyclotron.

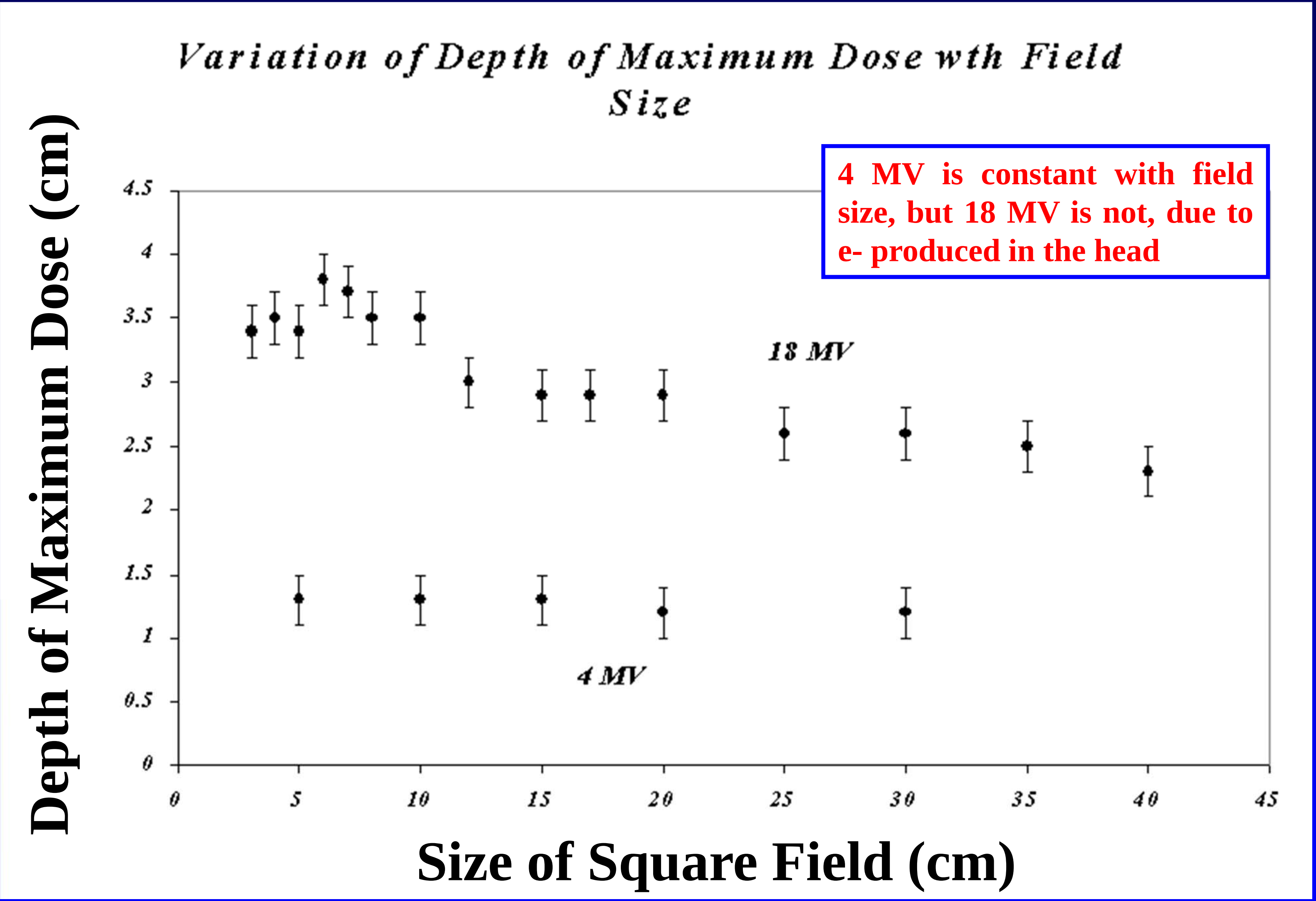

Variation of Percent Depth Dose with Energy
Percent Depth Dose
Depth in Water (cm)
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
45
18 MV
10 MV
6 MV
4 MV
Change in d max
With energy


Variation of Percent Depth Dose at Field Size for 4 MV Photons
Percent Depth Dose
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
Depth in Water (cm)
30x30
10x10
5x5
Little change in d_{max}
Increase due to scatter radiation

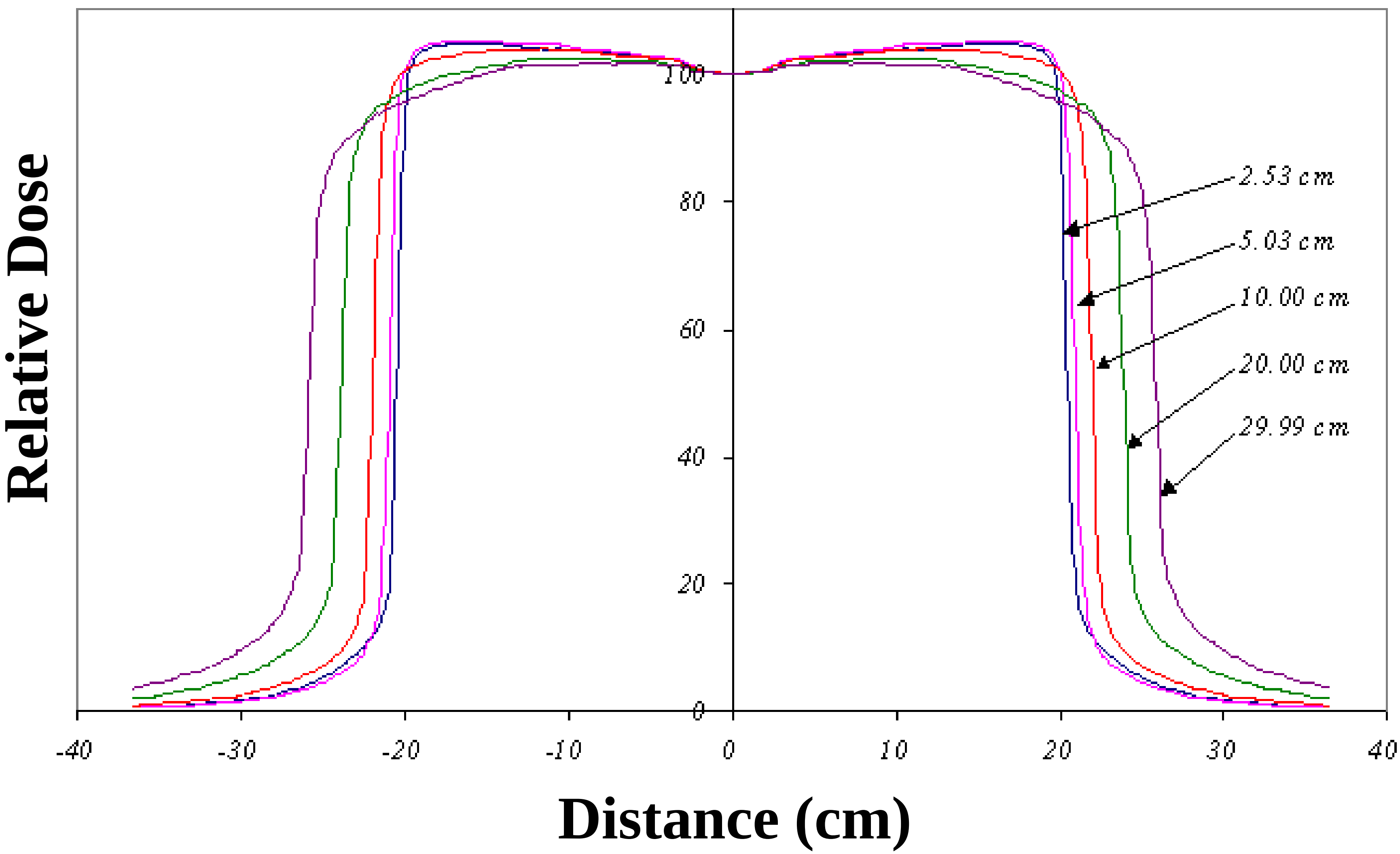


Variation of Percent Depth Dose at Field Size for 18 MV Photons
Percent Depth Dose
Depth in Water (cm)
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
45
40x40
10x10
4x4
Significant change in d_{max} with field size
Much less side scatter at high energies


Variation of Maximum Depth Dose with Energy
Depth of Maximum Dose (cm)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
4 MV
6 MV
10 MV
18 MV
Beam Energy (MV)
As one would expect, dmax increases with energy(range of secondary electrons), but is not linear


Variation of Depth of Maximum Dose wth Field Size
4 MV is constant with field size, but 18 MV is not, due to e- produced in the head
Depth of Maximum Dose (cm)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
18 MV
4 MV
0
5
10
15
20
25
30
35
40
45
Size of Square Field (cm)

Beam Profiles for a 40x40 Field at 18 MV




Thank you for your attention!

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