Charged Particle Interactions, Electron Beams, and Proton Beams

Eric Elder, PhD

EMORY | WINSHIP CANCER INSTITUTE

A Cancer Center Designated by the National Cancer Institute

Radiation Therapy

Incident Ionizing Photon

↓

Fast electron

↓

Ion radical

↓

Free radical

↓

Chemical changes from the breakage of bonds

↓

Biological Effects

Eric Hall, Radiobiology

Charged Particle Interactions

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$$

Coulomb's Law

Electron Interactions

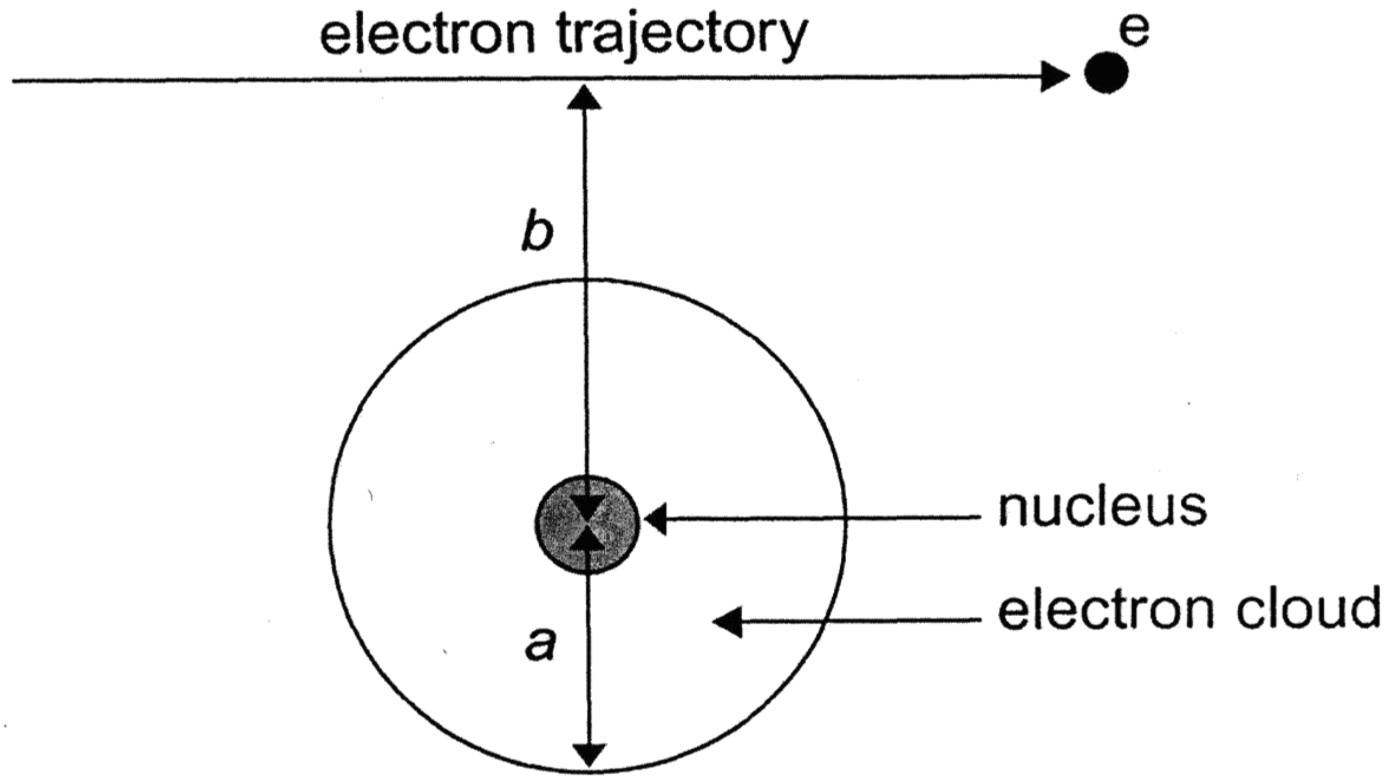
- Elastic Collisions – No change in total kinetic energy before and after collision

- Inelastic Collisions – Kinetic energy lost to:
  - Atomic electrons (excitation or ionization)
  - Nuclei (X-Ray production – bremsstrahlung)

Collisional Losses – excitation or ionization

Radiative Losses – bremsstrahlung

Electron Interactions

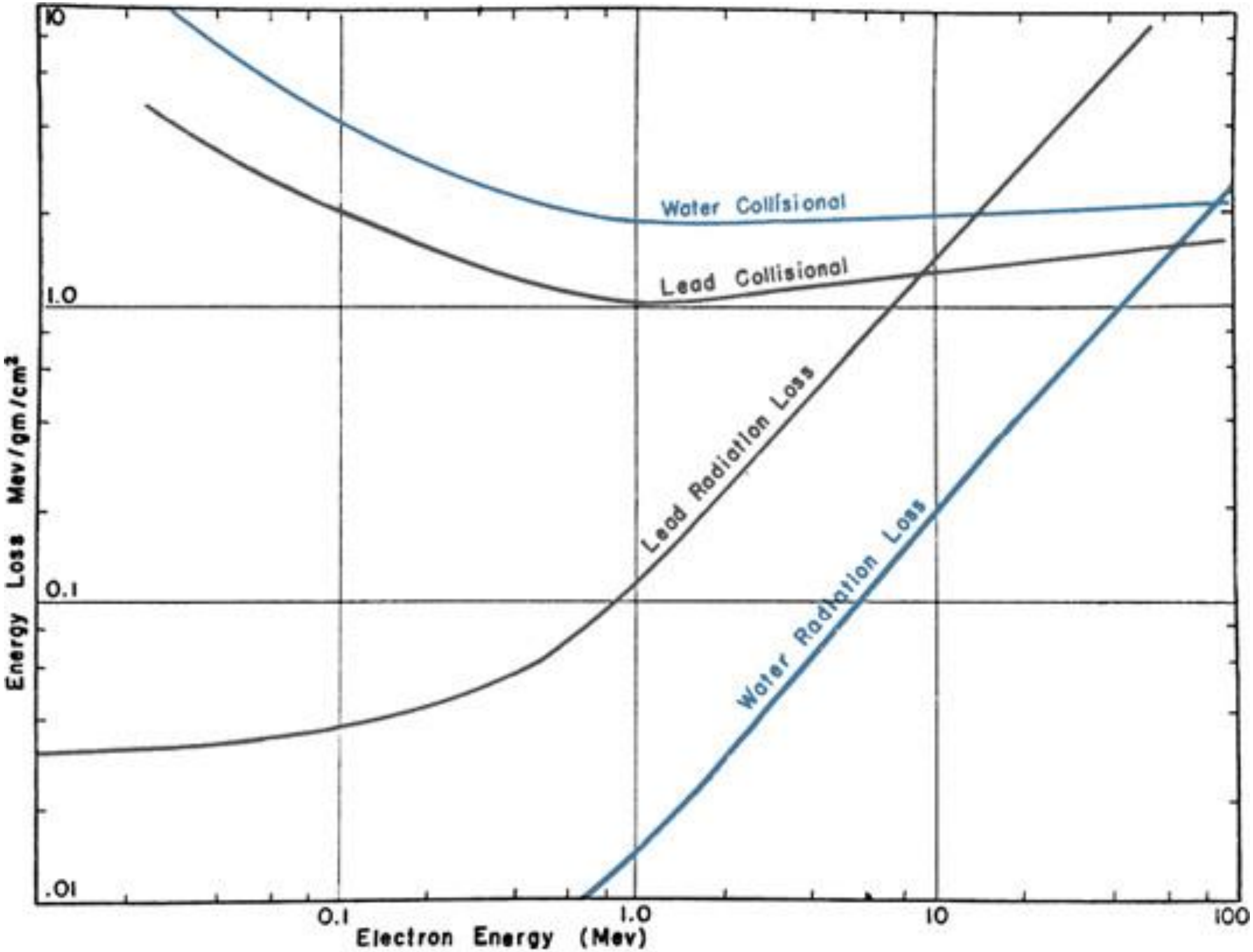


Stopping Power

- Stopping Power = Energy lost per unit path length in the medium → MeV/cm
- Mass Stopping Power = Stopping power divided by density → $MeV/cm^2/g$

$$\left(\frac{S}{\rho}\right)_{Total} = \left(\frac{S}{\rho}\right)_{Col} + \left(\frac{S}{\rho}\right)_{Rad}$$

Mass Stopping Power



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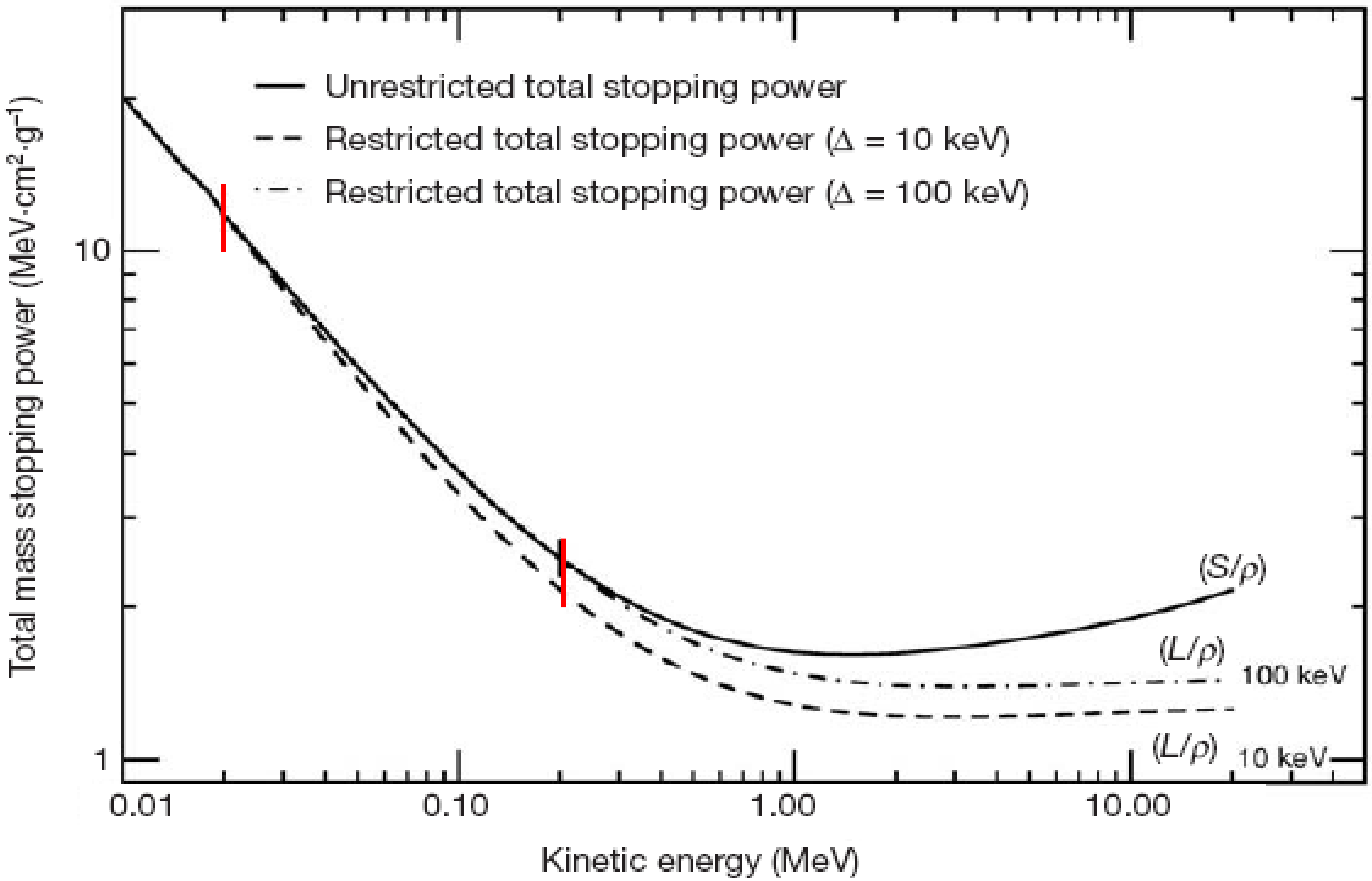
Absorbed Dose

$$D_{med} \equiv \Phi_E \cdot (S/\rho)_{col,\Delta}$$

$$D = \int_{\Delta}^{E_0} \Phi_E \cdot (S/\rho)_{col,\Delta} \cdot dE$$

Restricted Stopping Power



from ICRU Report No. 37

Absorbed Dose from another Medium

$$\frac{D_{med2}}{D_{med1}} = \frac{\Phi_E \cdot (L/\rho)_{col,\Delta,med2}}{\Phi_E \cdot (L/\rho)_{col,\Delta,med1}}$$

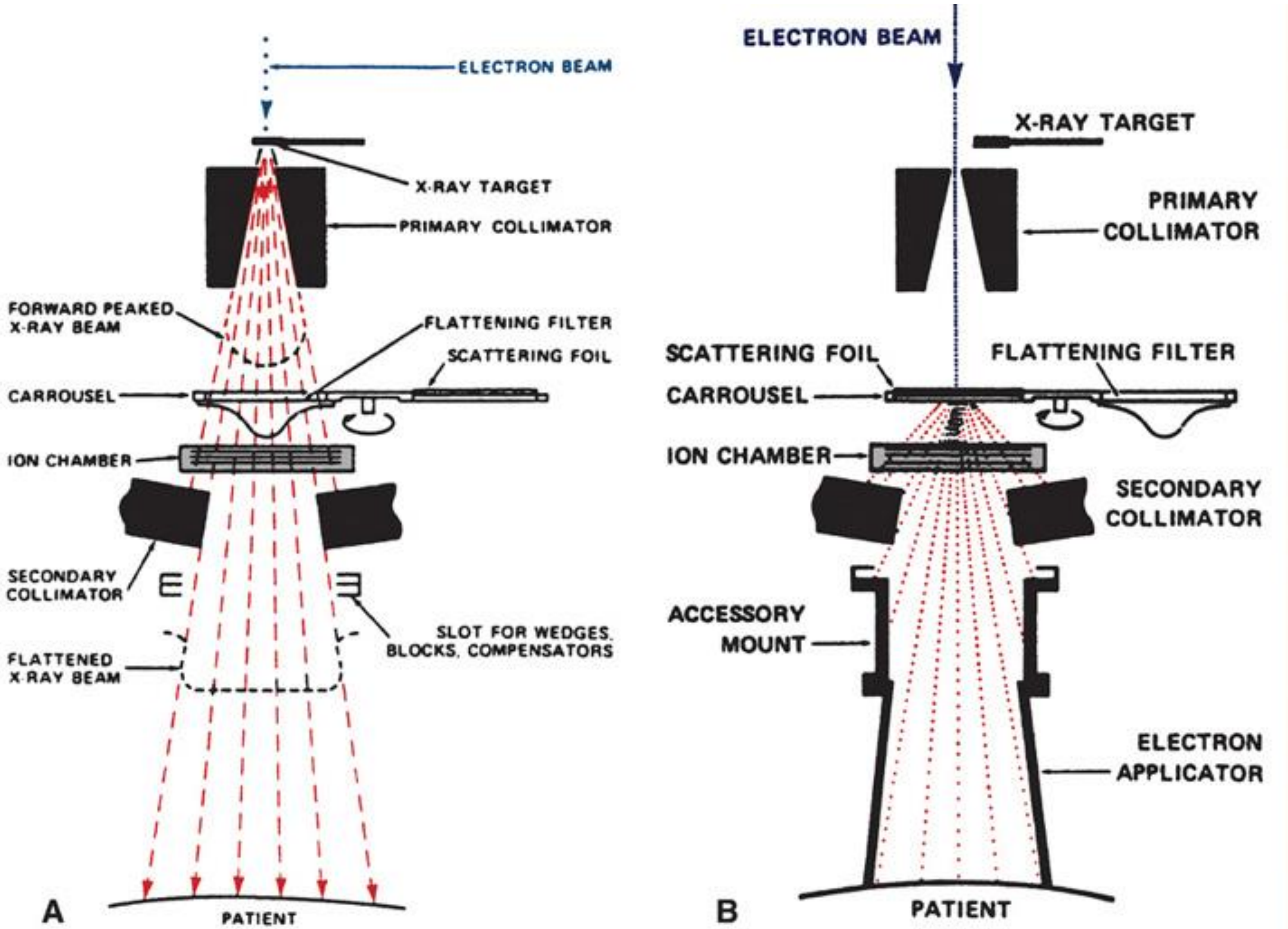
$$D_{med2} = D_{med1} \frac{(L/\rho)_{col,\Delta,med2}}{(L/\rho)_{col,\Delta,med1}}$$

$$D_{med2} = D_{med1} (L/\rho)^{med2}_{med1}$$

Electron Scattering

- Electrons scatter due to Columbic interactions with (mostly) nuclei
- The spatial and directional distribution of electrons is approximately Gaussian
- The mass angular scattering power is proportional to Z^2/E^2

Electron Beam Collimation



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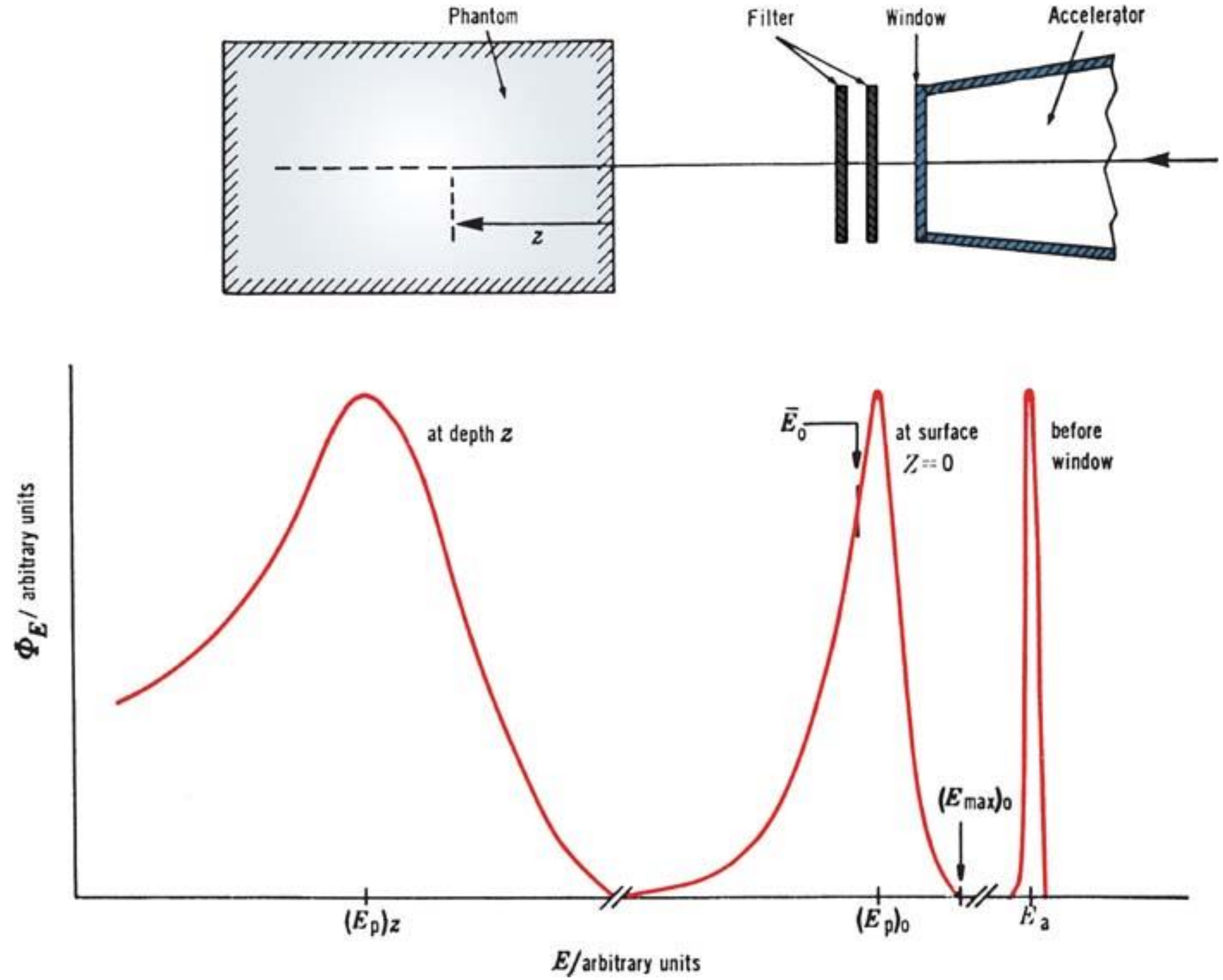
Electron Beam Energy



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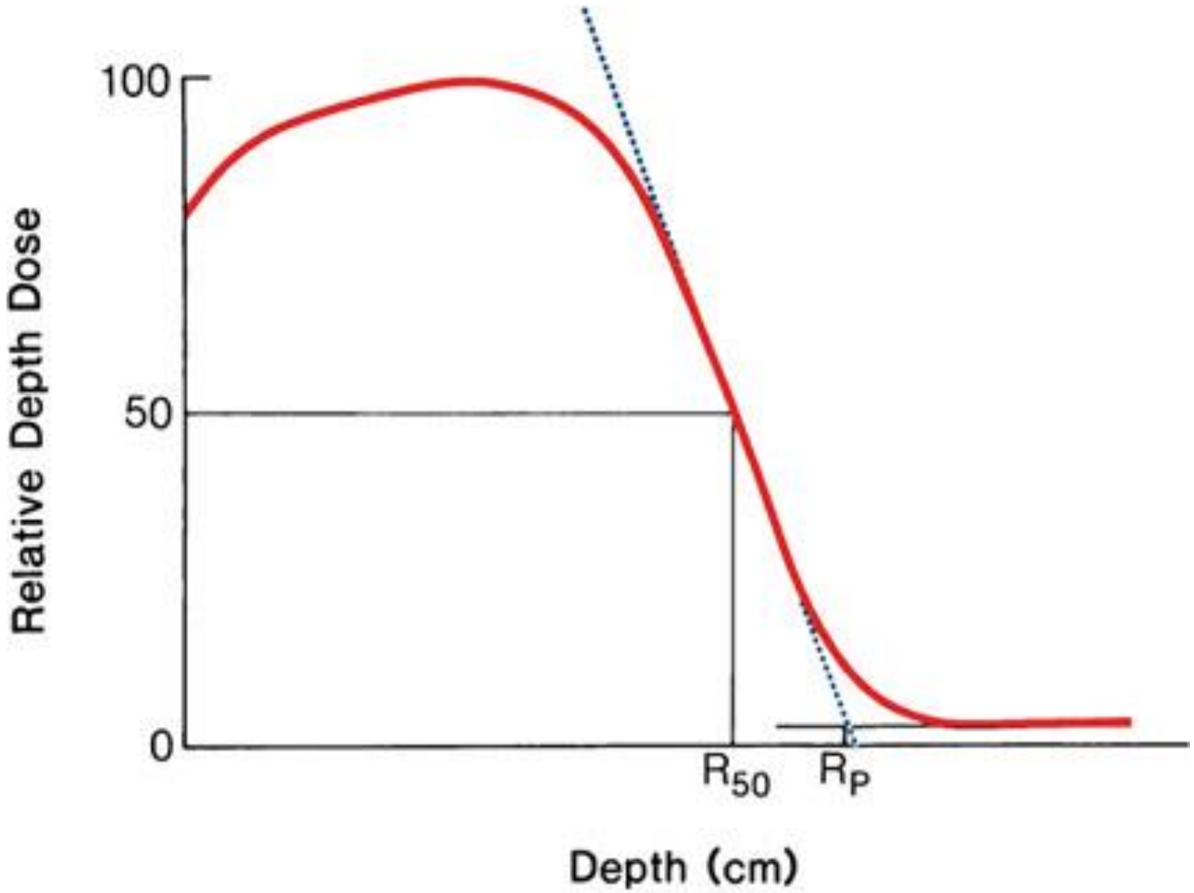
Electron Beam Energy



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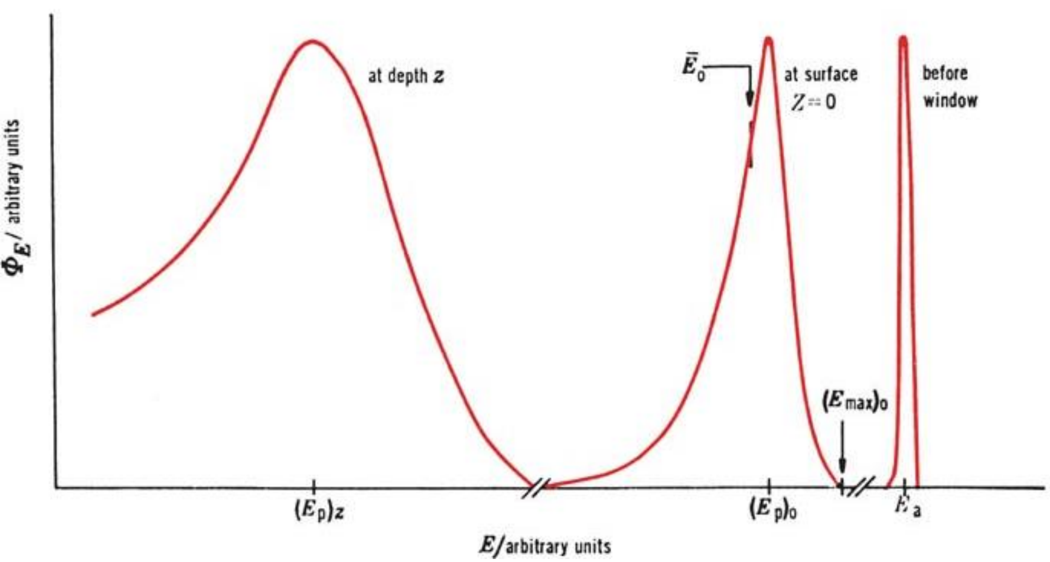
Electron Beam Energy at Surface

Most Probable Energy

$$(E_p)_0 = C_1 + C_2 R_P + C_3 (R_P)^2$$



Mean Energy

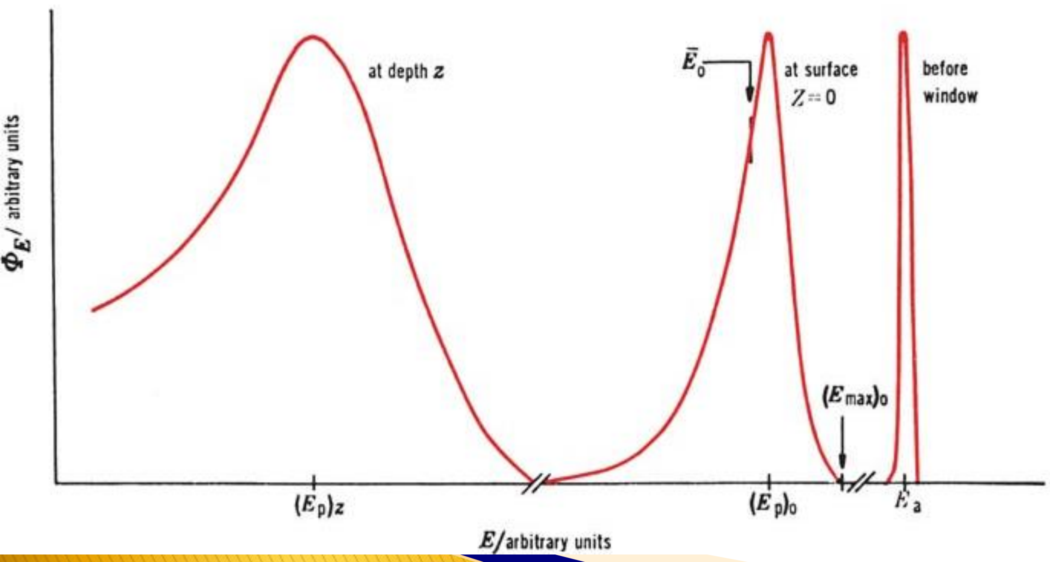
$$\overline{E}_0 = C_4 \cdot R_{50}$$

Where $C_4 = 2.33$ MeV/cm

Electron Beam Energy at Depth z

Most Probable Energy at Depth z

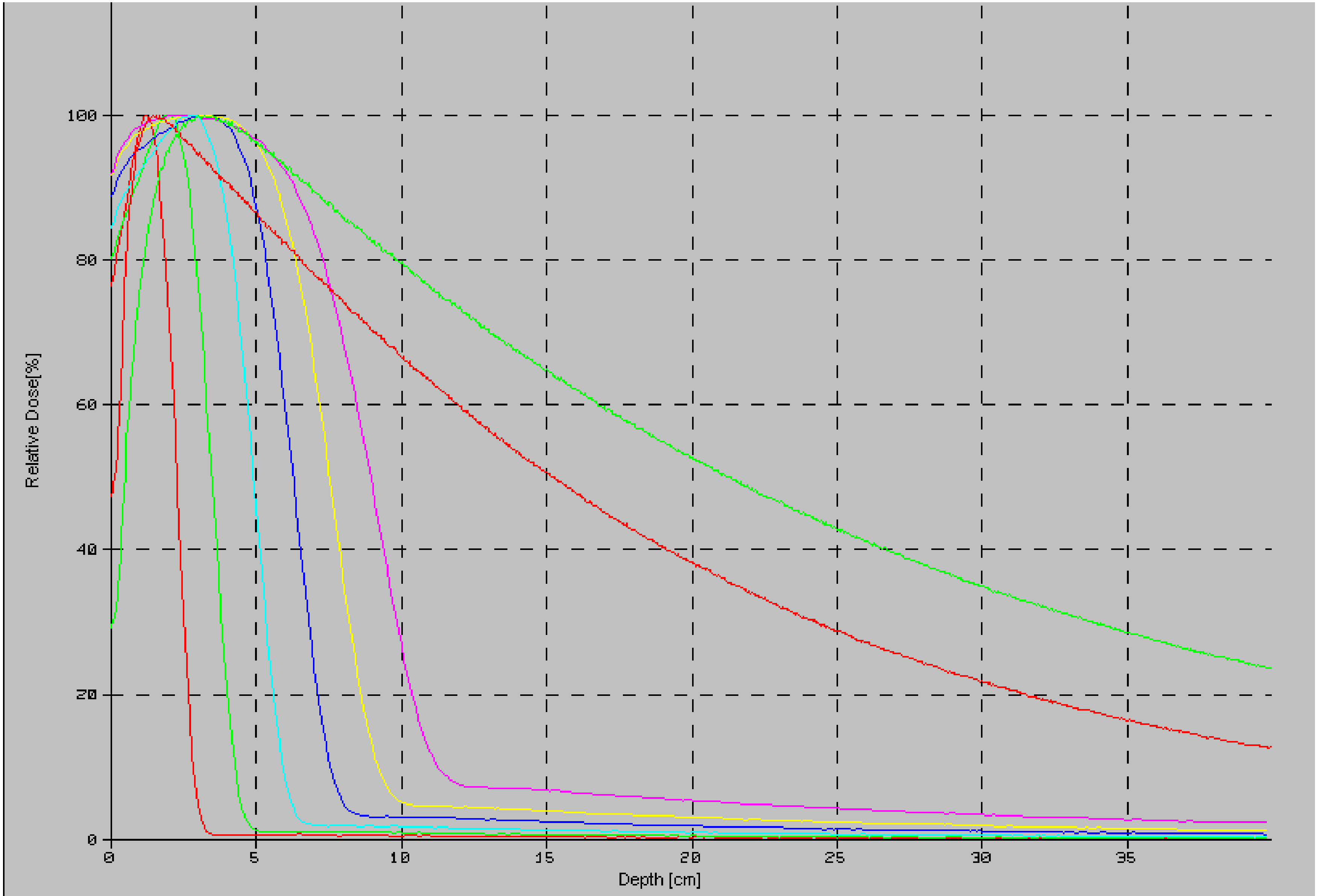
$$\left(E_p\right)_z = \left(E_p\right)_0 \left(1 - \frac{z}{R_p}\right)$$



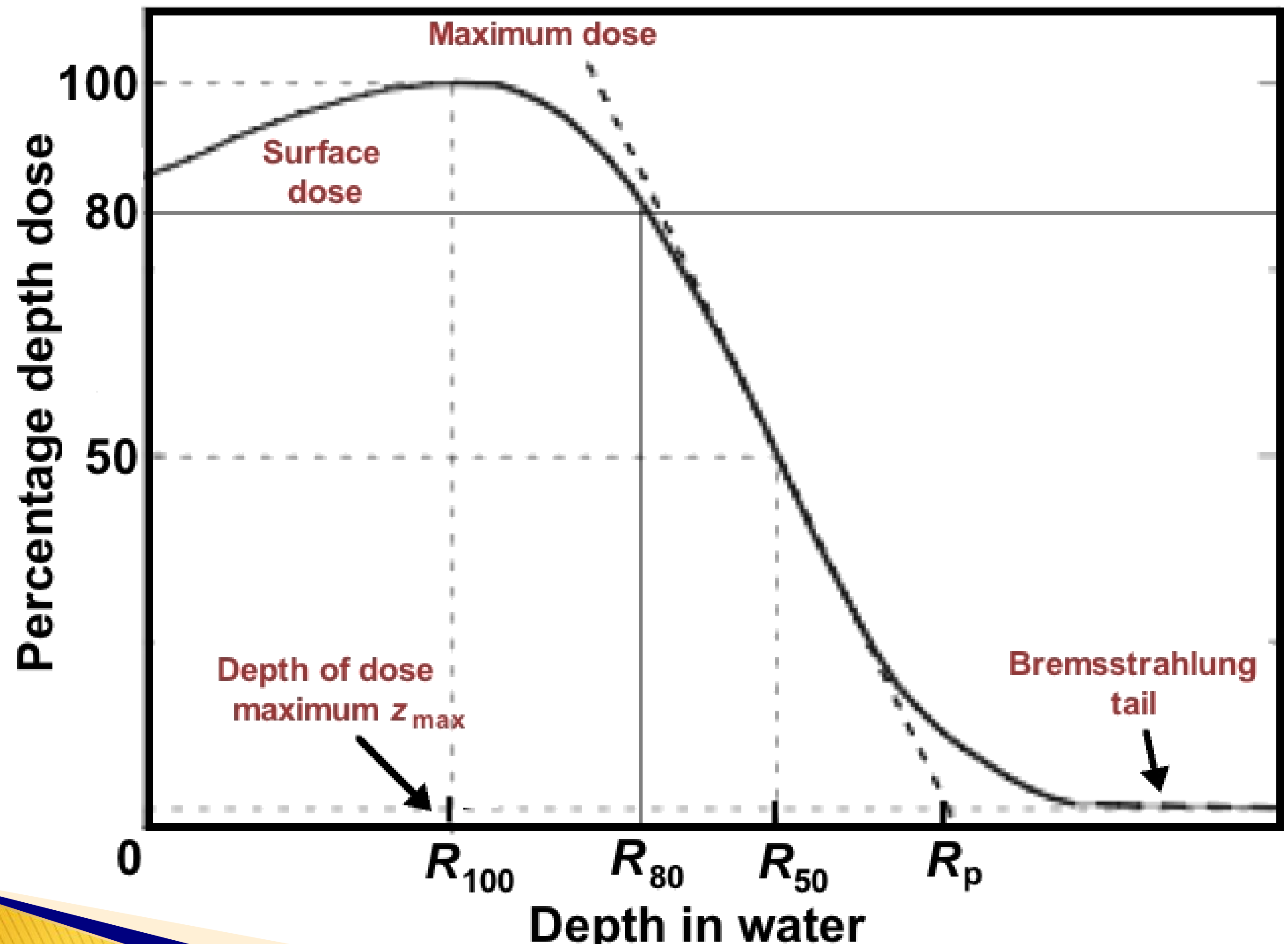
Mean Energy at z

$$\bar{E}_z = \bar{E}_0 \left(1 - \frac{z}{R_p}\right)$$

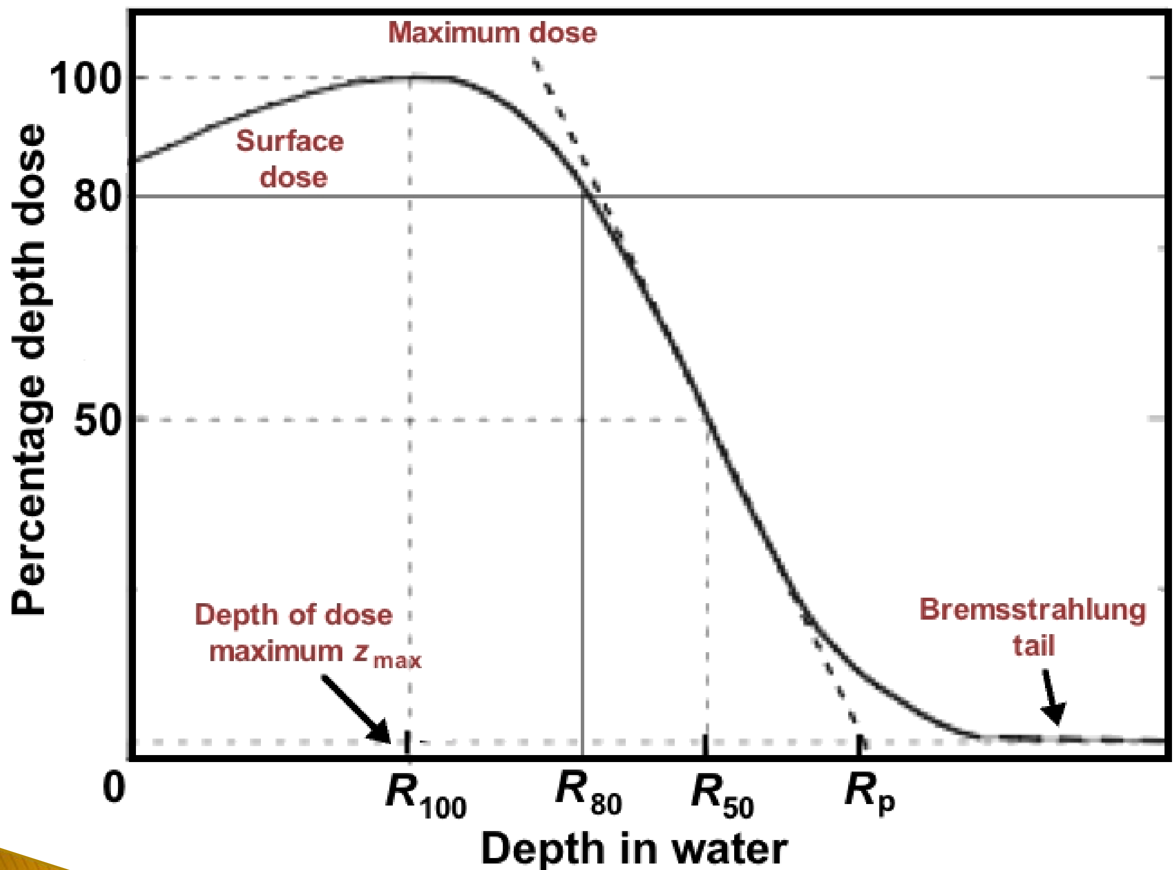
Electron Depth Dose Curves



Percentage Depth Dose Curve



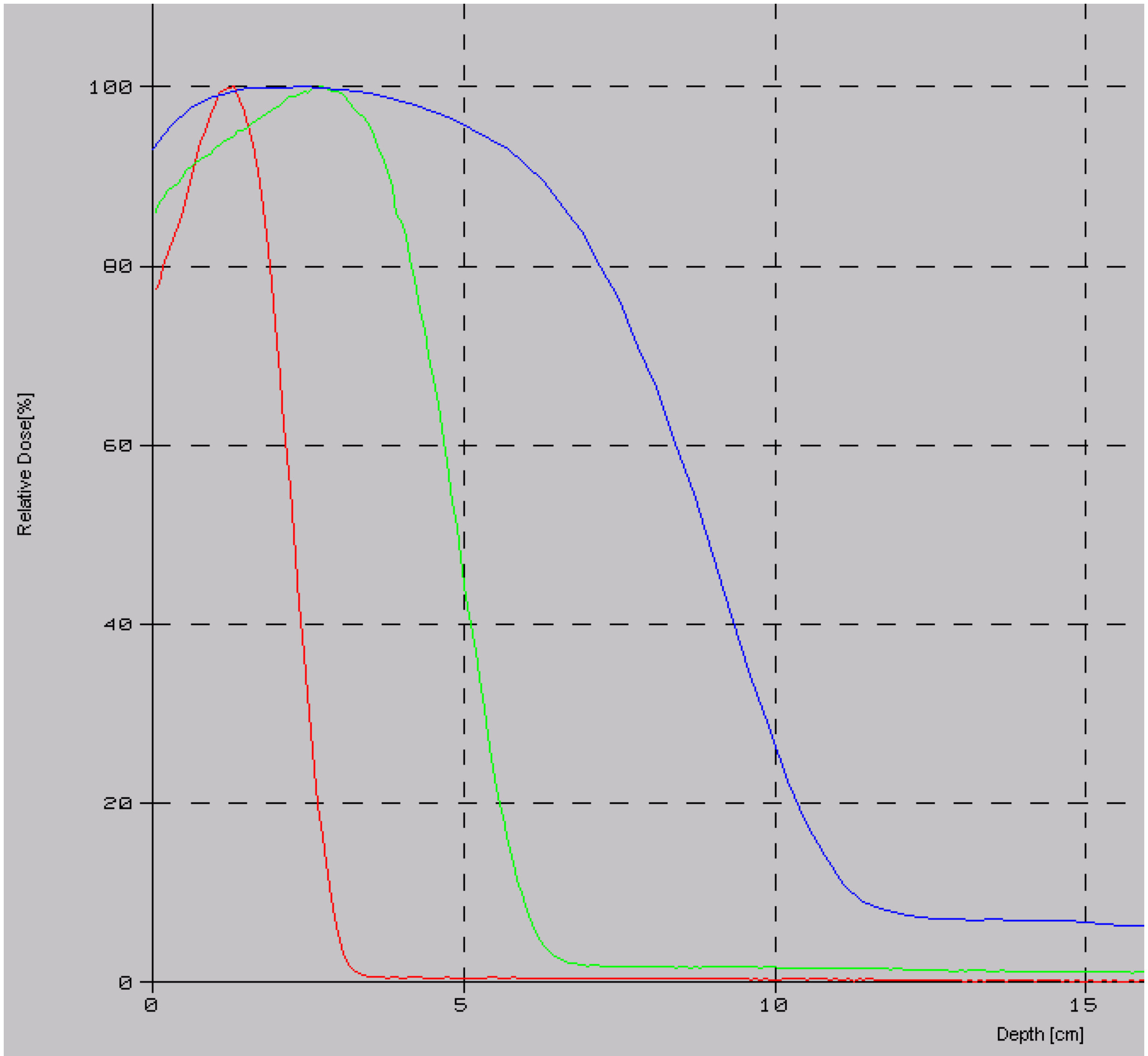
Electron PDD Rules of Thumb



Ranges in cm
E in MeV

- $R_p = E/2$
- $R_{80} = E/3$
- $R_{90} = E/4$
- $R_{100} \approx E/5$

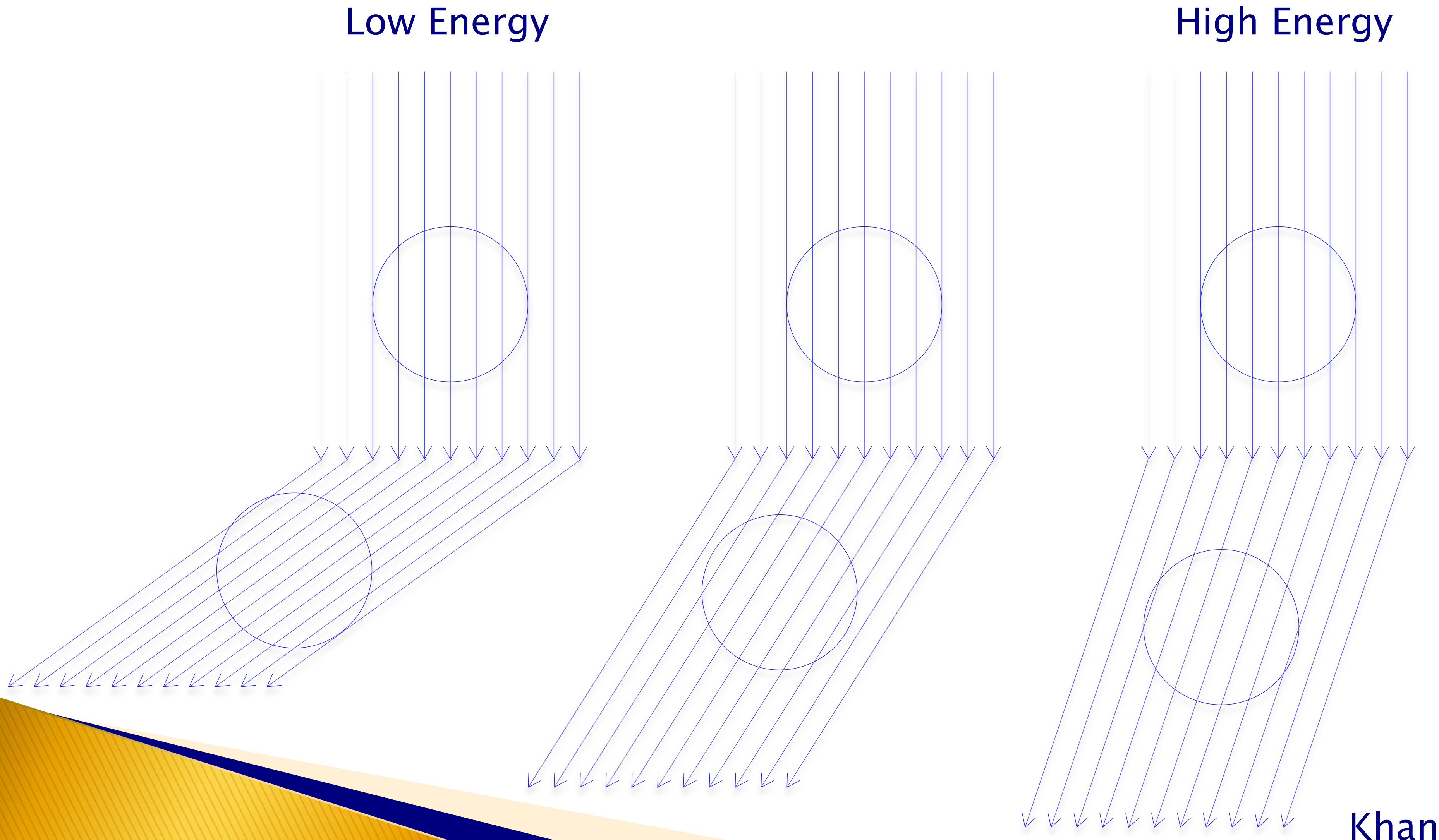
Electron Surface Dose



6 MeV
12 MeV
22 MeV

Why does surface dose increase with increasing electron energy?

Electron Surface Dose



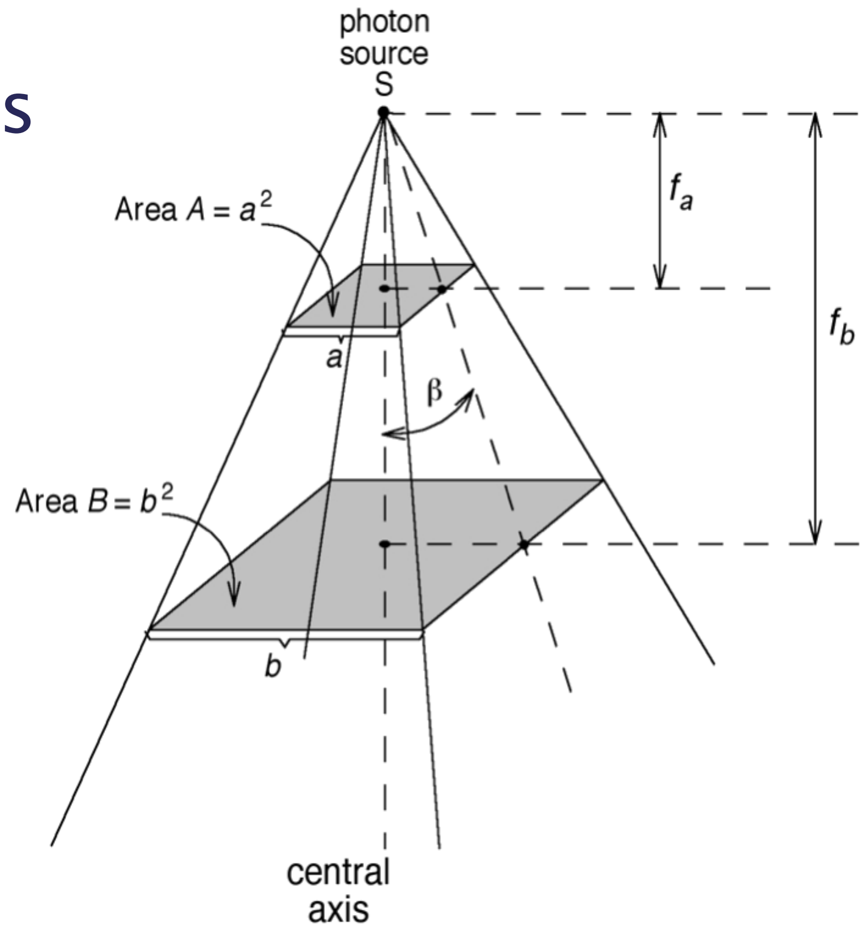
Photon Extended SSD

We assume that $N_{tot} = const$, i.e., no photon interactions take place in air. Therefore:

$$\frac{a/2}{f_a} = \frac{b/2}{f_b} \Rightarrow \frac{a/2}{b/2} = \frac{a}{b} = \frac{f_a}{f_b}$$

$$B\phi_B = A\phi_A$$

$$\frac{\phi_B}{\phi_A} = \frac{A}{B} = \frac{a^2}{b^2} = \frac{f_a^{\,2}}{f_b^{\,2}}$$



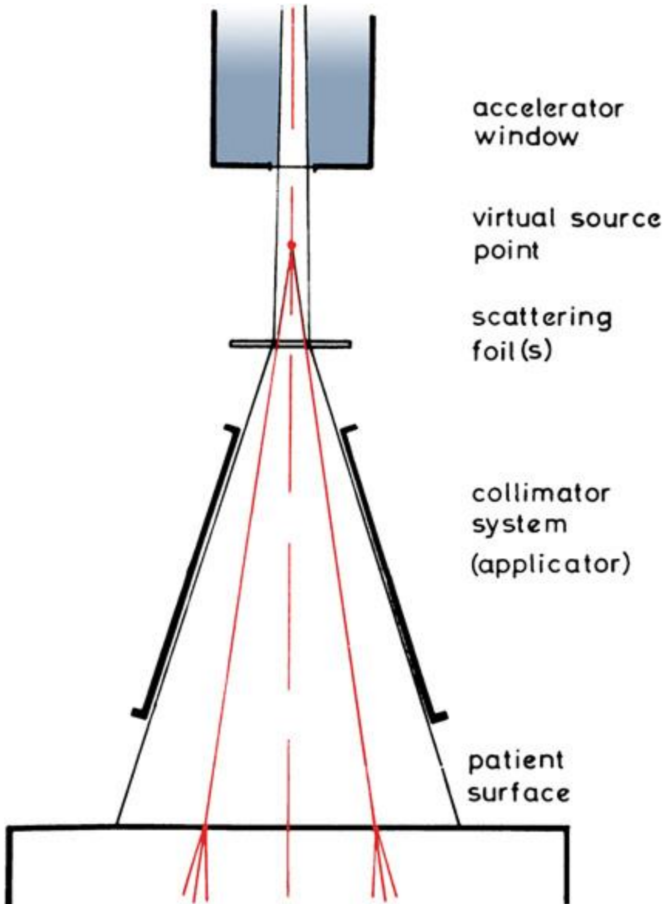
IAEA

Extended SSD

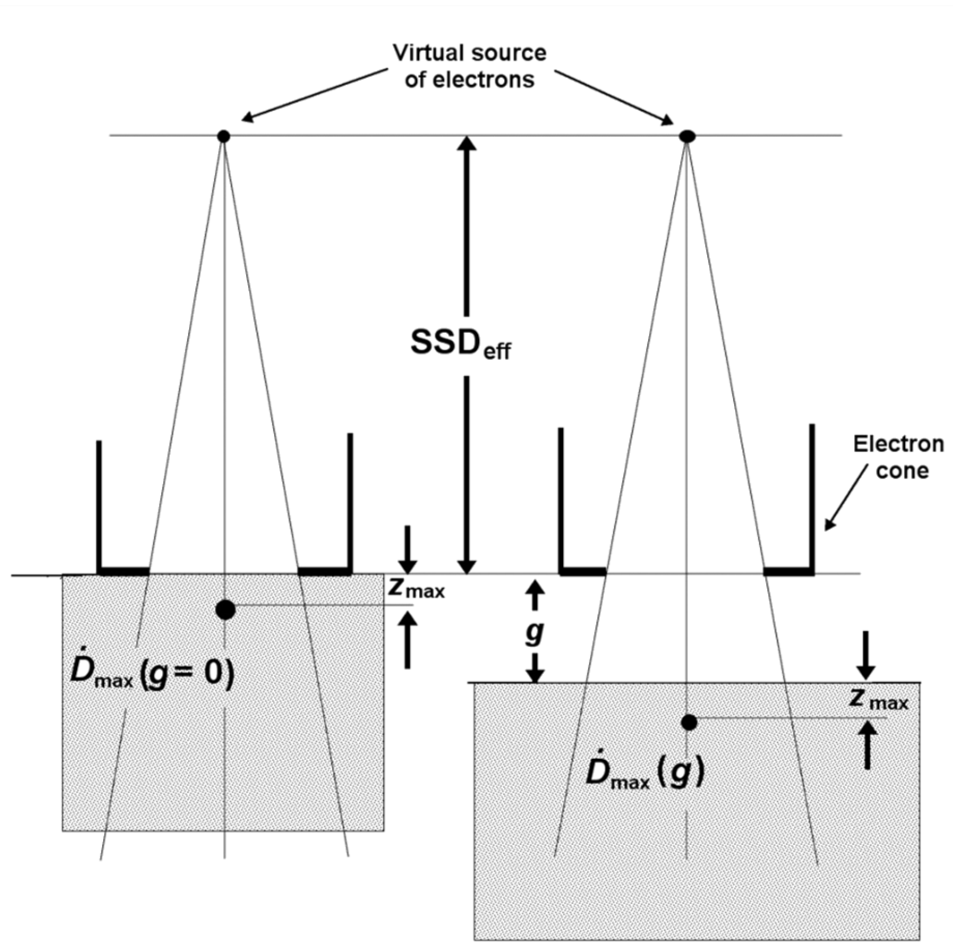
- Output is reduced
  - Inverse Square Law
  - Loss of side scatter equilibrium (electrons are "flaring out" in air, and can not get back to d_{max})

- Two methods for accounting for Extended SSD
  - Virtual Point Source
  - Effective SSD

Virtual Point Source



Effective SSD



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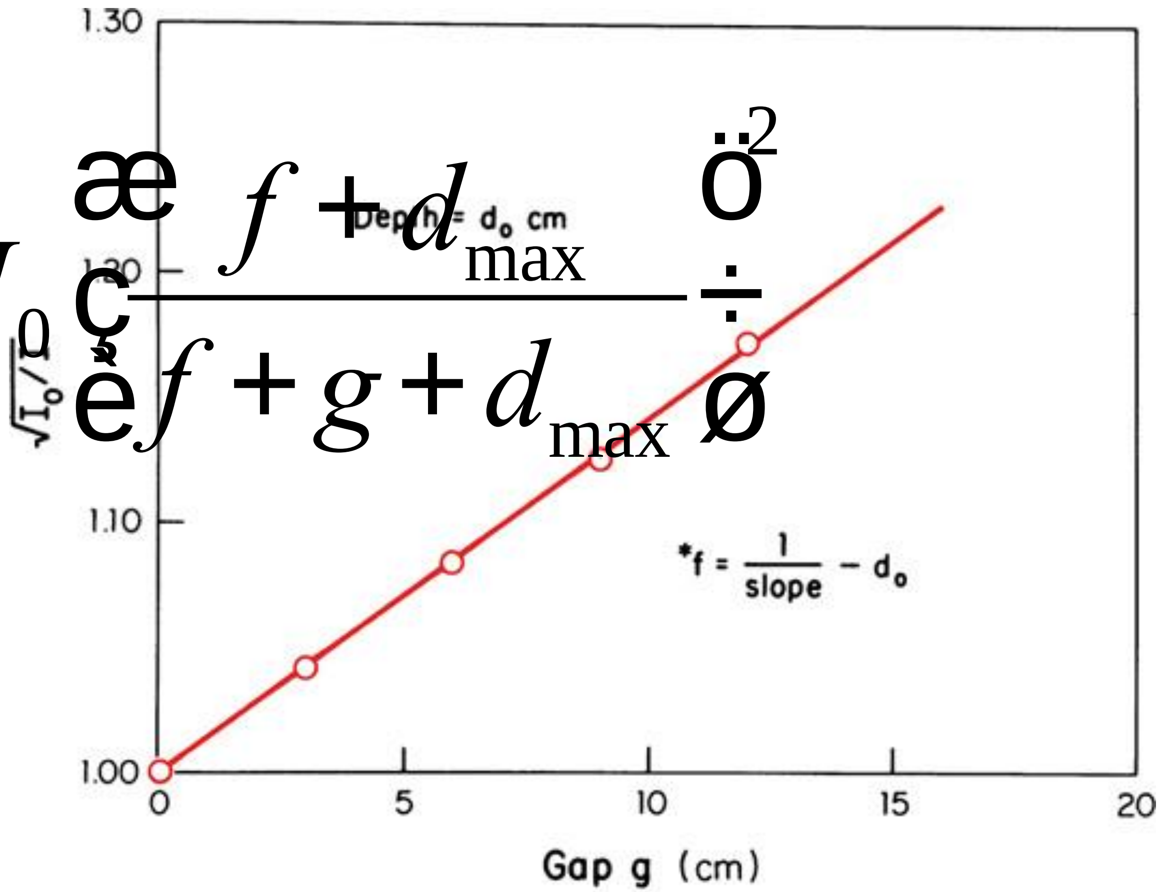
Calculating Effective SSD

$$\frac{I_0}{I_g} = \left(\frac{f + d_m + g}{f + d_m}\right)^2$$

$$\sqrt{\frac{I_0}{I_g}} = \left(\frac{f + d_m + g}{f + d_m}\right)$$

$$\sqrt{\frac{I_0}{I_g}} = \frac{1}{f + d_m} g + 1$$

$$I_g = I_0 \left(\frac{f + d_{\max}}{f + g + d_{\max}}\right)^2$$



Effect of Extended SSD on Isodoses

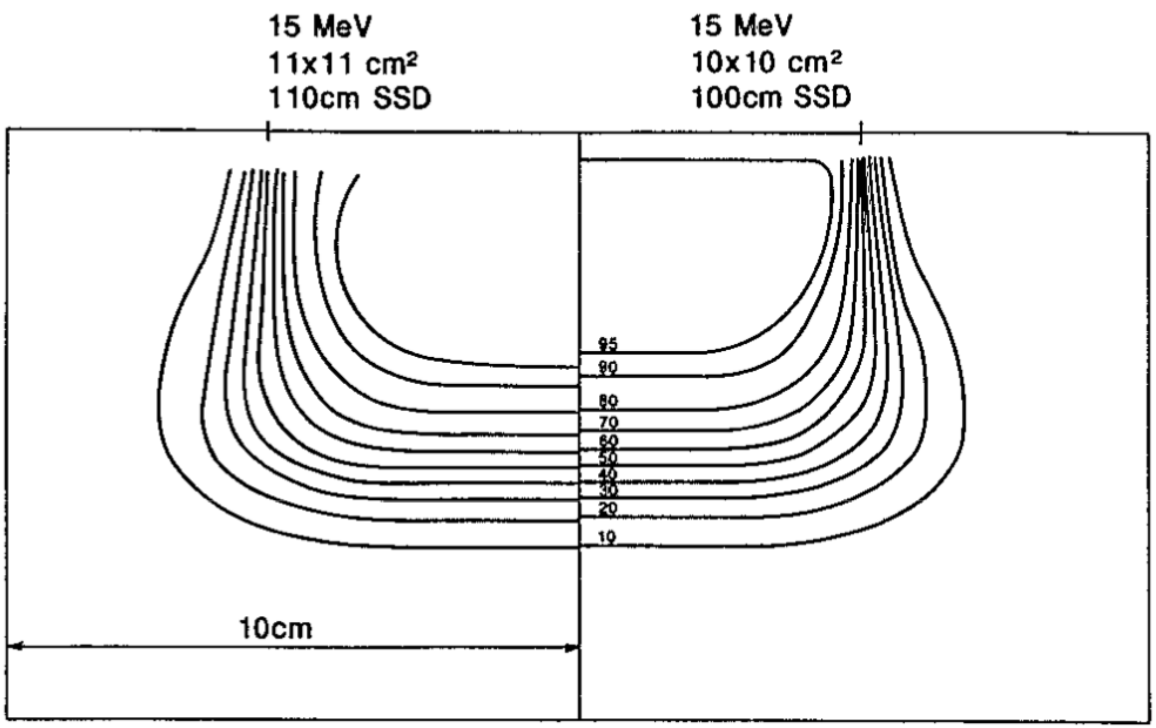
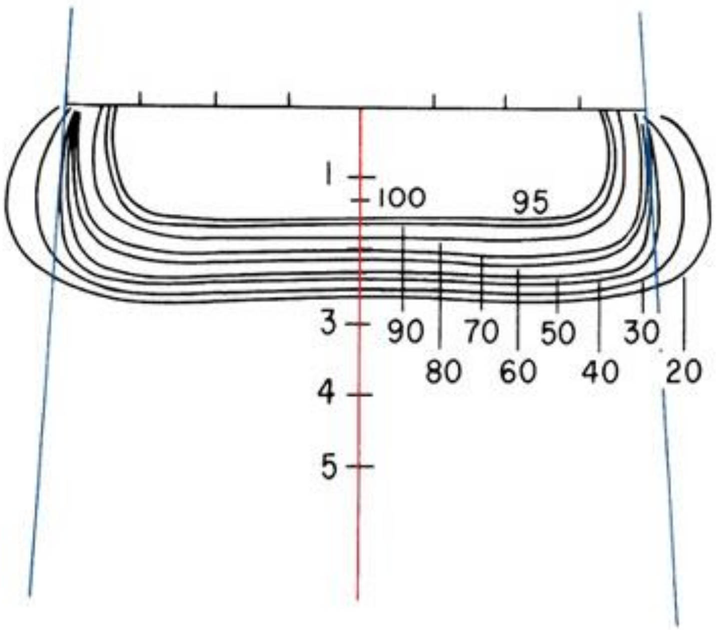
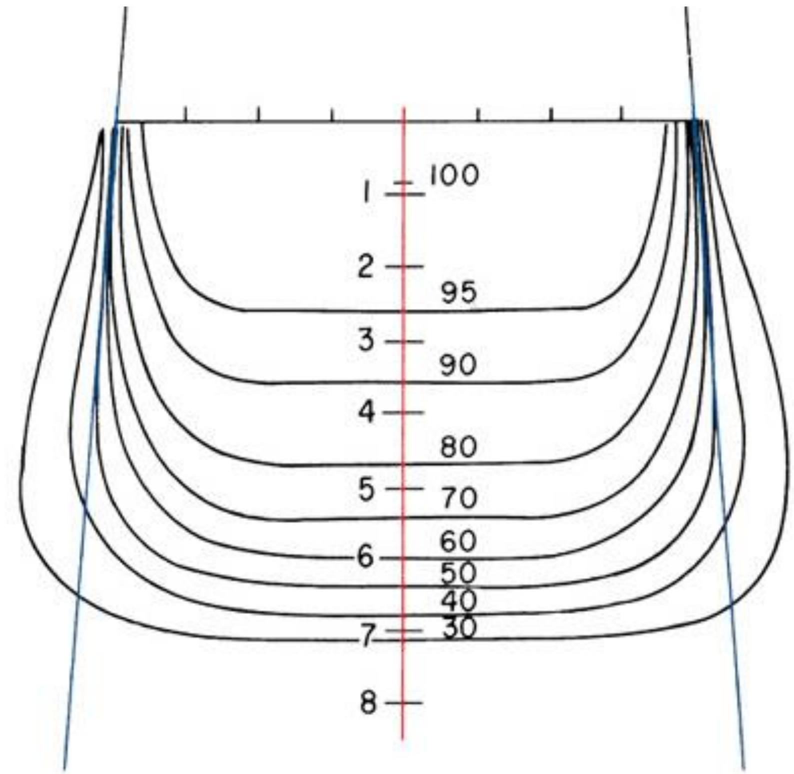


FIG. 25. Comparison of iso-ionization curves measured for nominal SSD as opposed to extended SSD conditions. [From Hogstrom *et al*. (1984).]

Isodose Curves



7-MeV Electron Beam
8-cm Circle, ∡1, F5, 50-cm TSD



18-MeV Electron Beam
8-cm Circle, ∡ 5, F7, 50-cm TSD.

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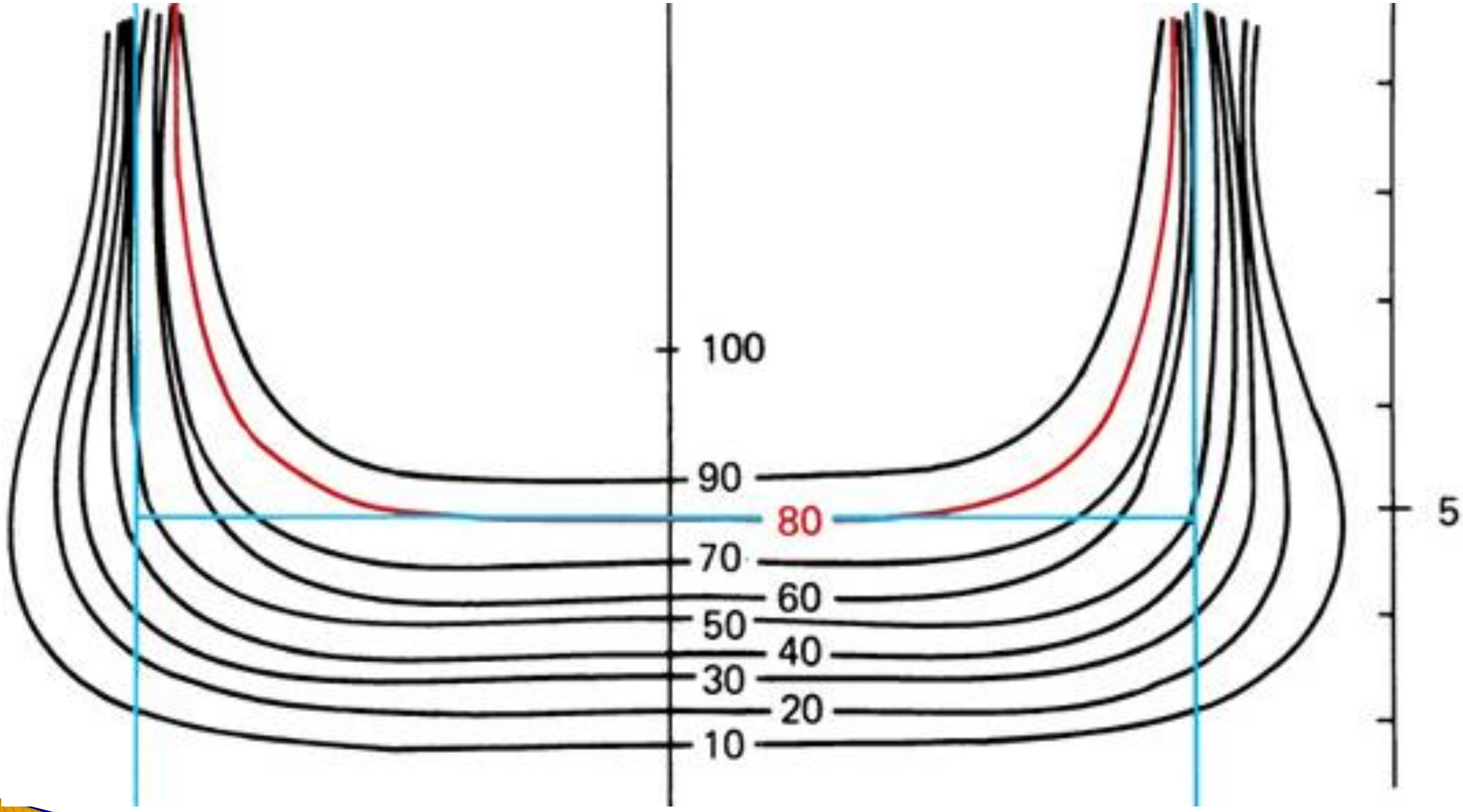
Isodose Curves



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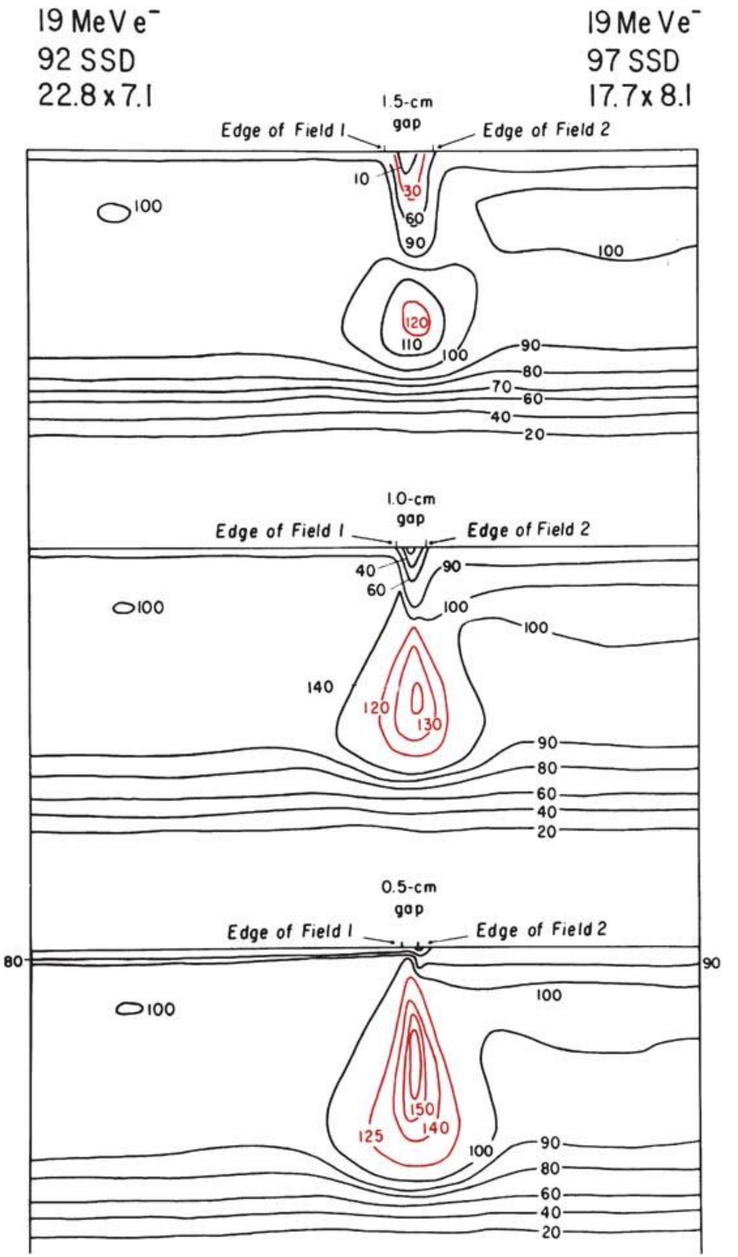
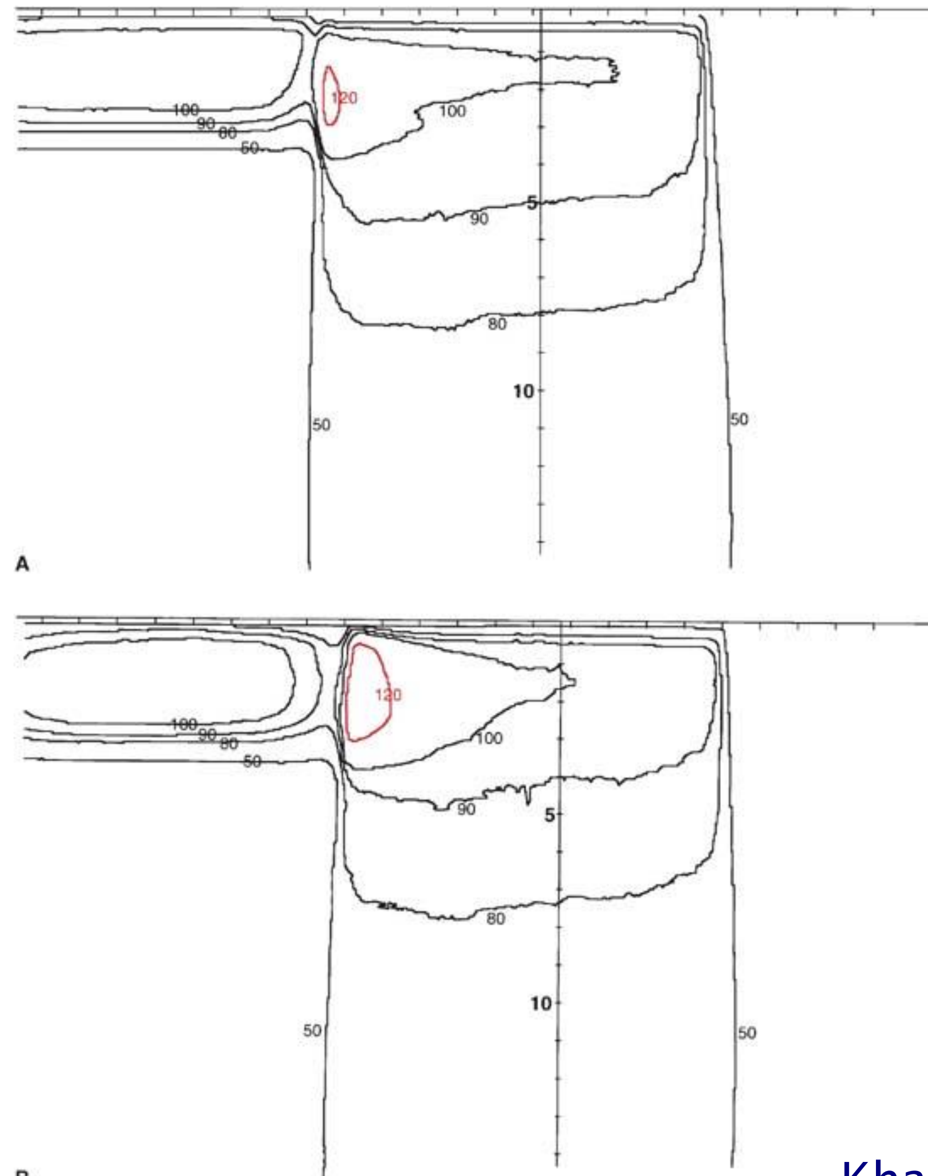
Adjacent Fields

- What is the treatment depth?
- What type and at what depth do dose heterogeneities occur?
- Where do dose heterogeneities occur with respect to the edge of the beams?
- What is the magnitude and volume of the dose heterogeneity?

Adjacent Electron Fields



Adjacent Electron-Photon Fields



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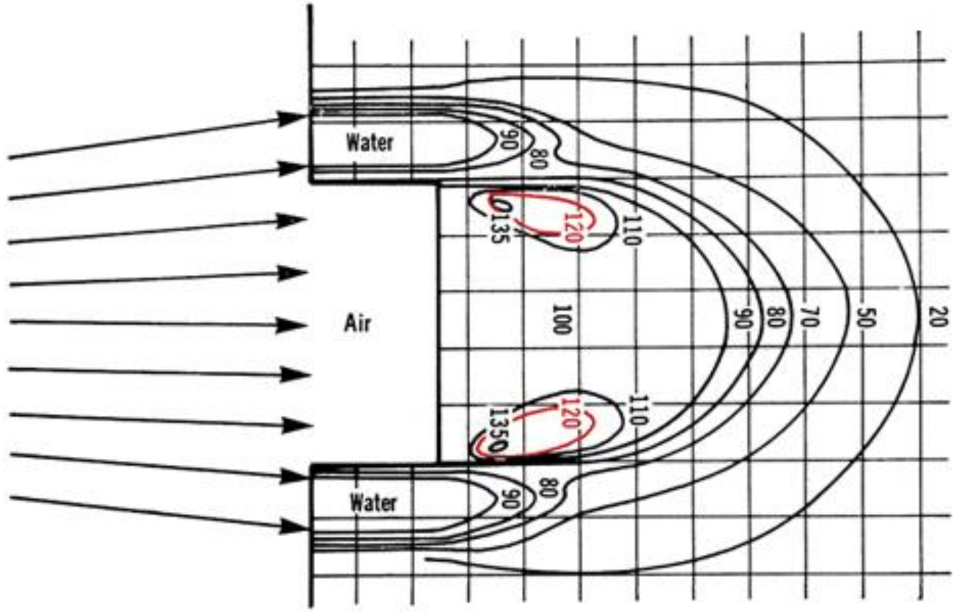
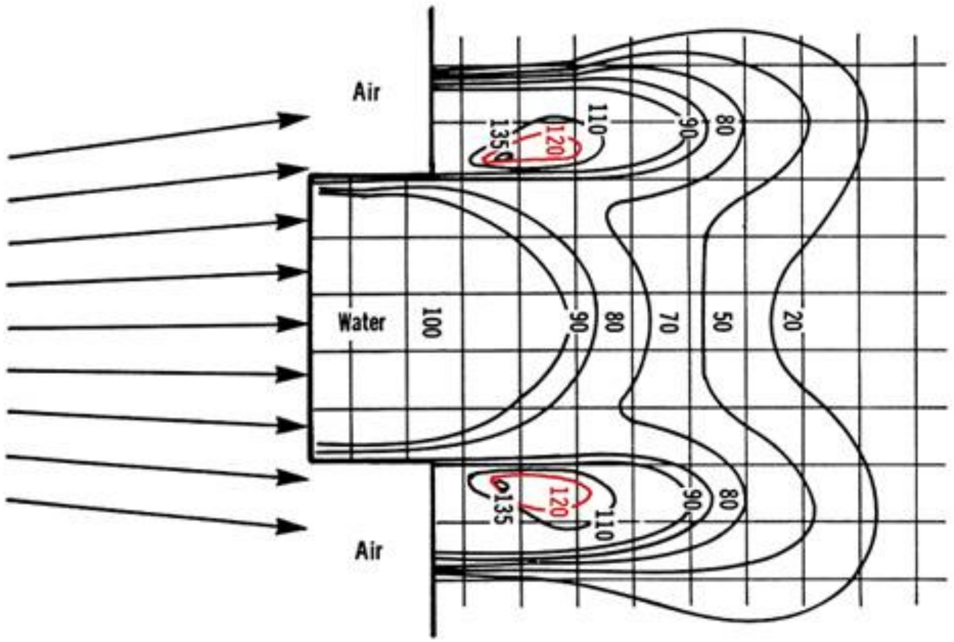
Missing Tissue

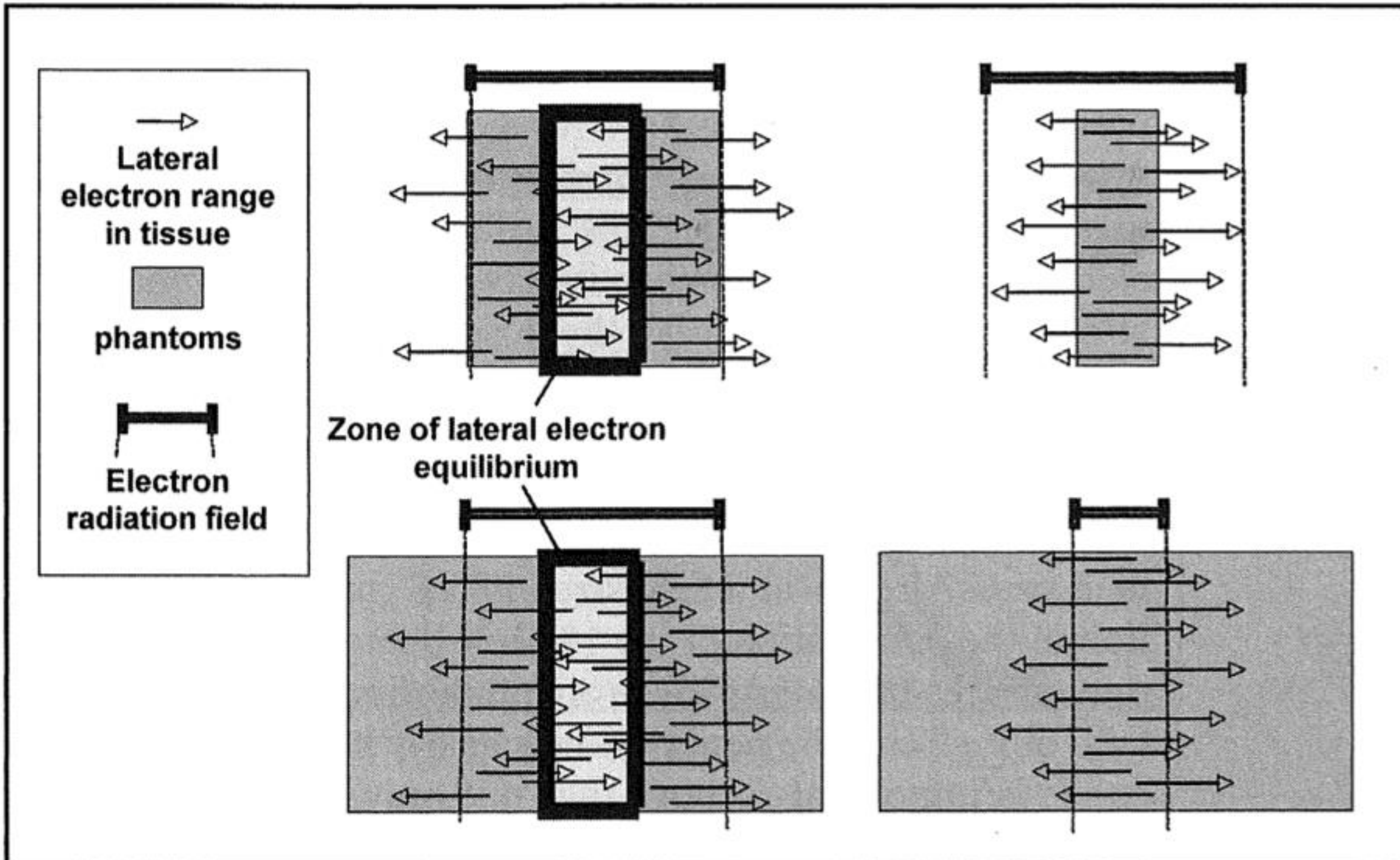




Field Shaping

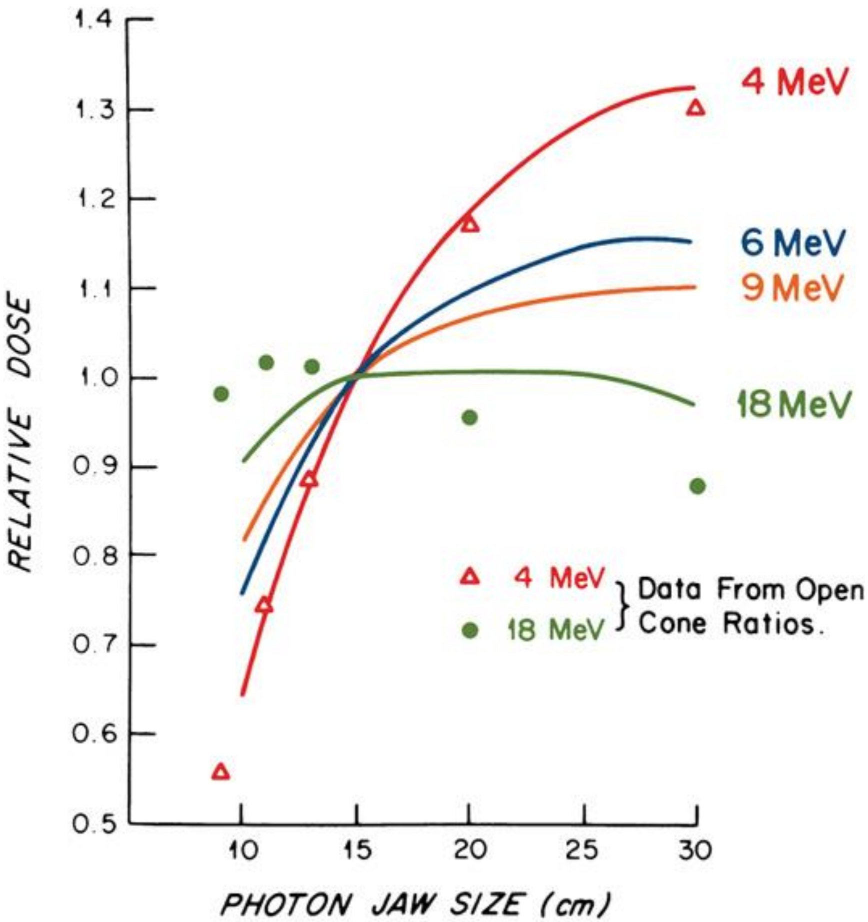
- Relative Dose Rates (Output) and PDDs are field size dependent
- Three types of field size: photon jaw settings, electron cone, and electron cutout
- Rule of thumb for cutouts: when field size is less than R_p changes in Output and PDD are possible

Lateral Electron Equilibrium

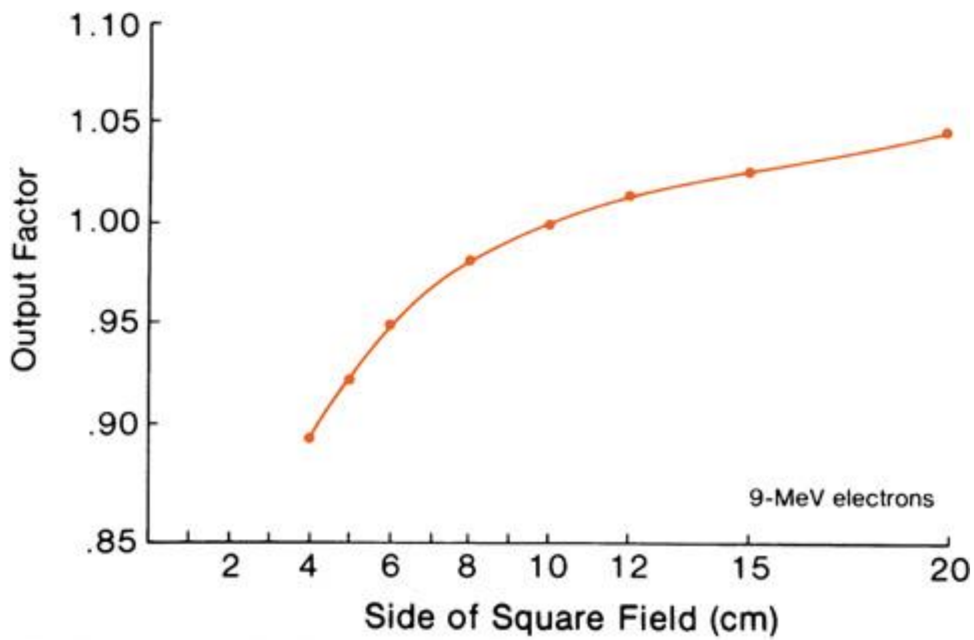


Metcalfe et al

Effect of Field Shaping on Output



Effect of Varying Photon Jaws on Relative Dose



Effect of Varying Field Size at Phantom on Relative Dose

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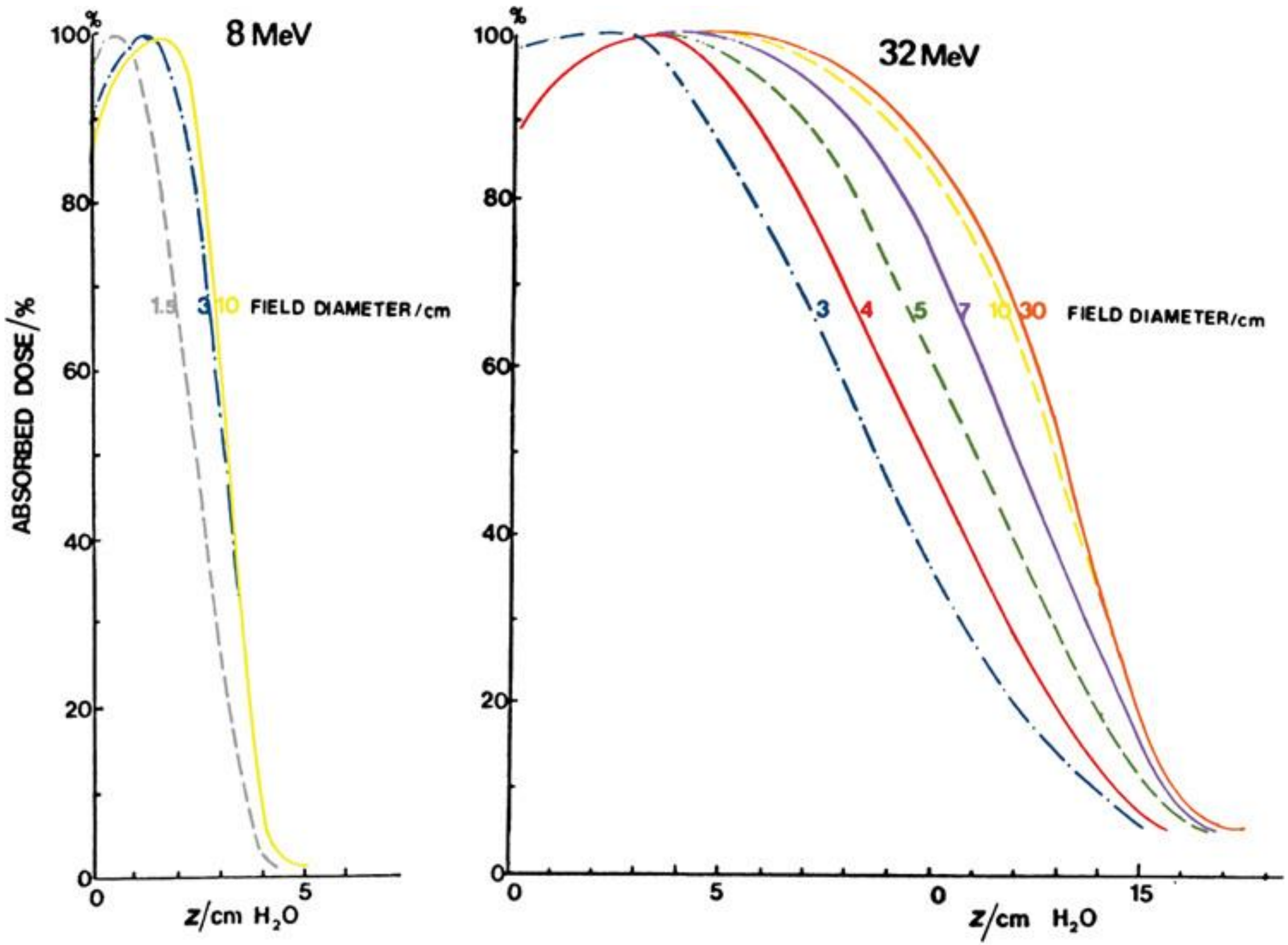
Effect of Field Shaping on PDD



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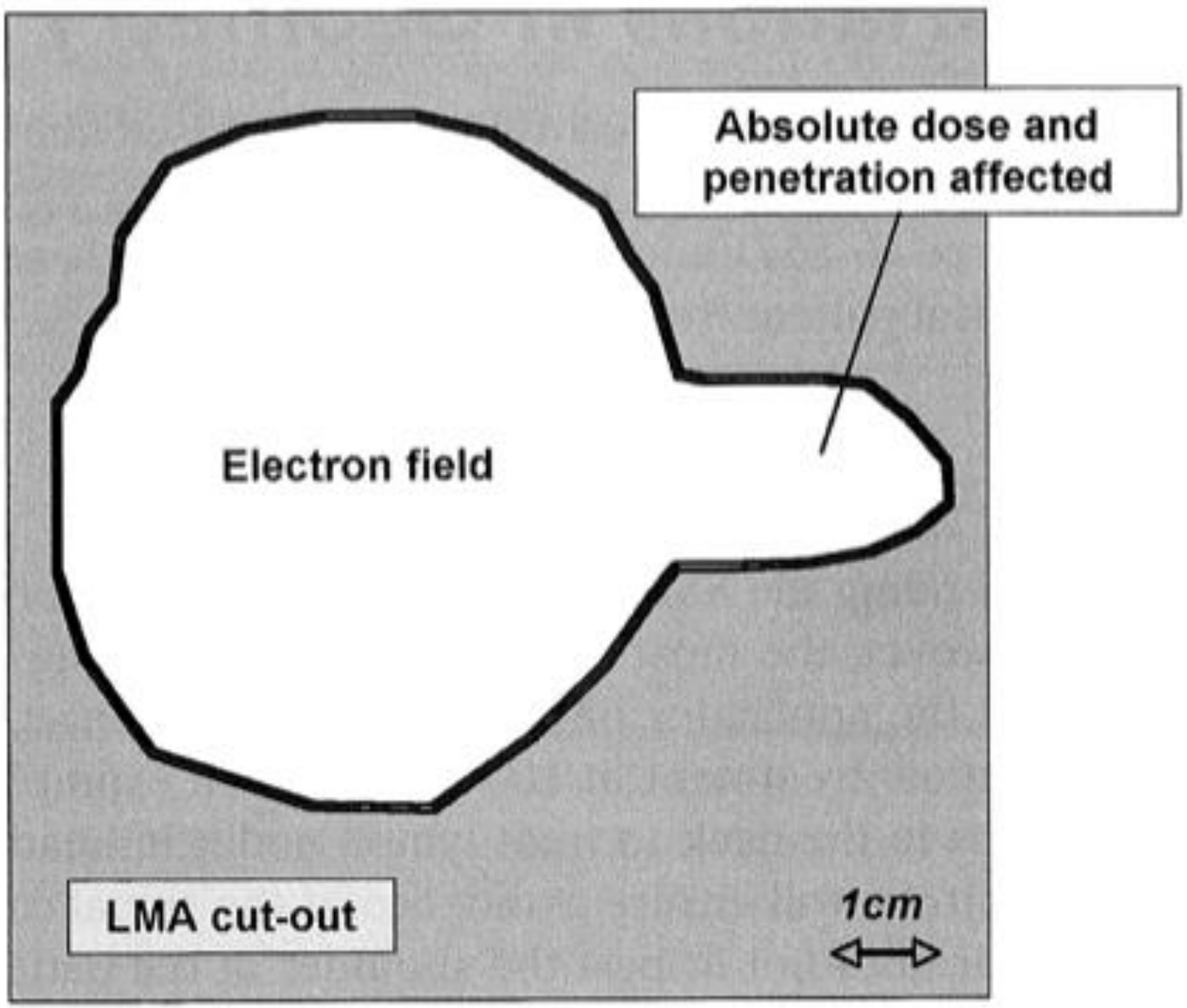
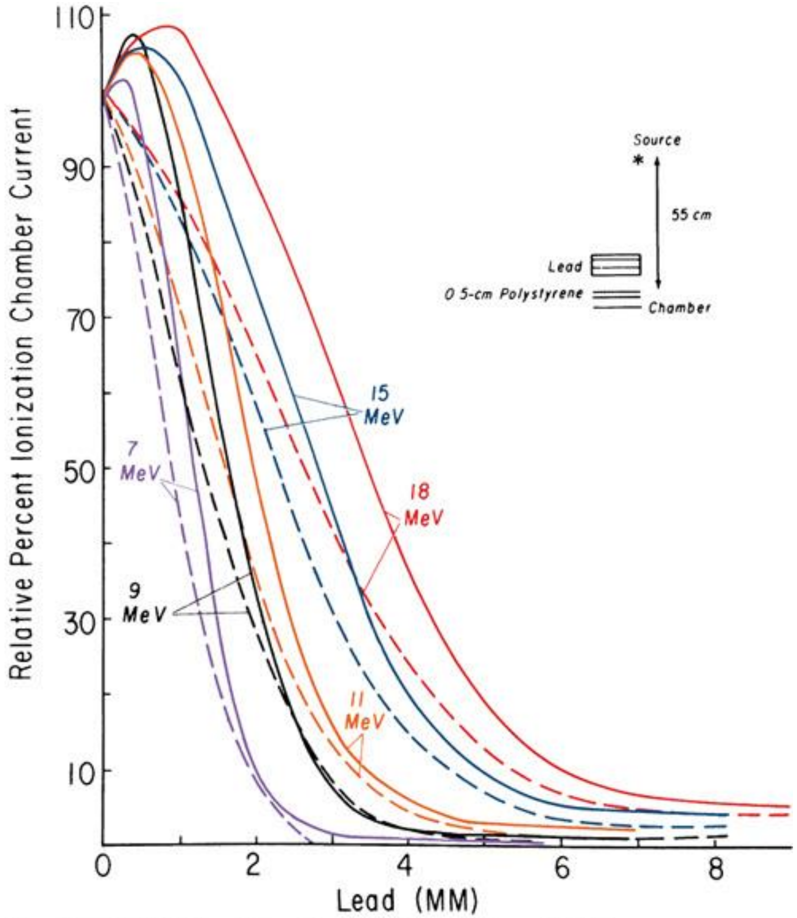
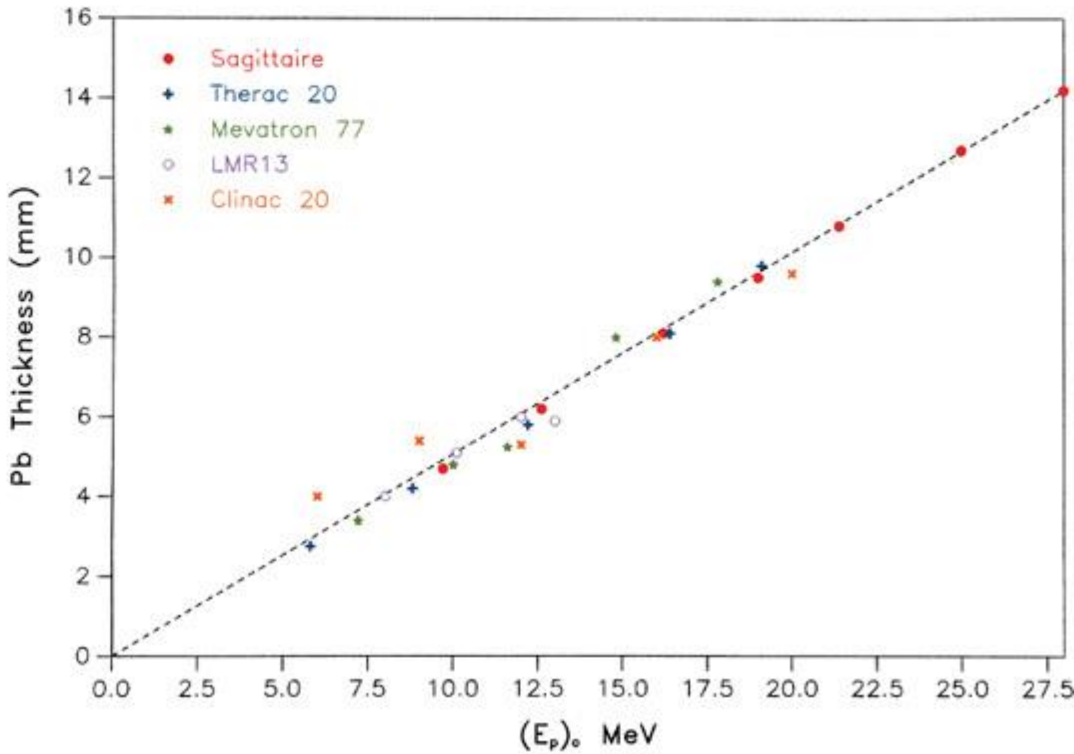


Metcalfe et al

Pb Shielding





Rule of Thumb – 1mm/2 MeV

Example – 3mm Pb for 6 MeV e^-

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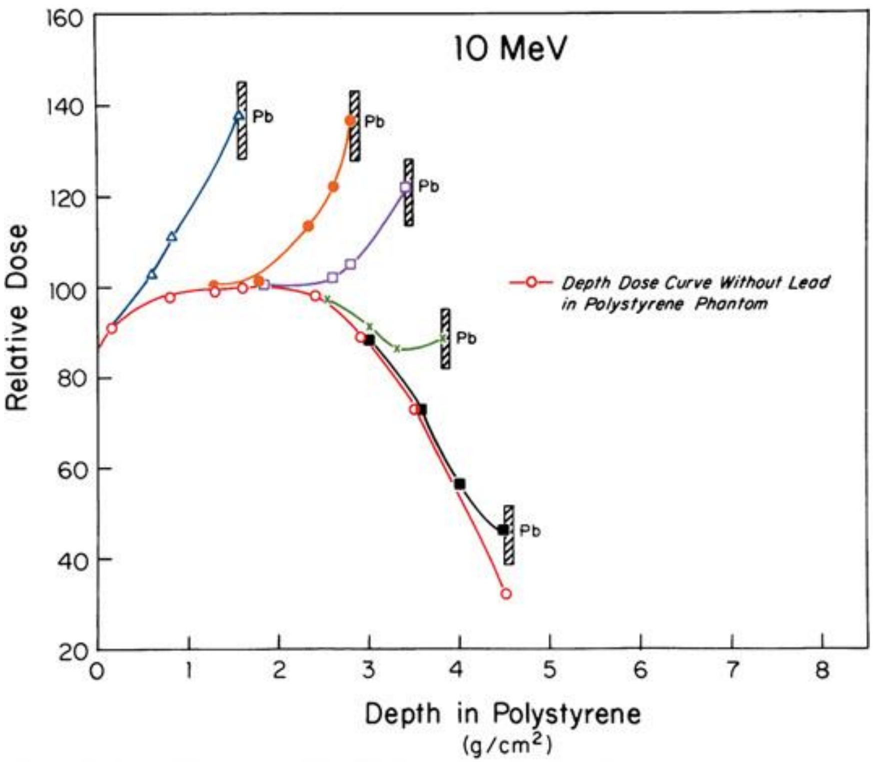
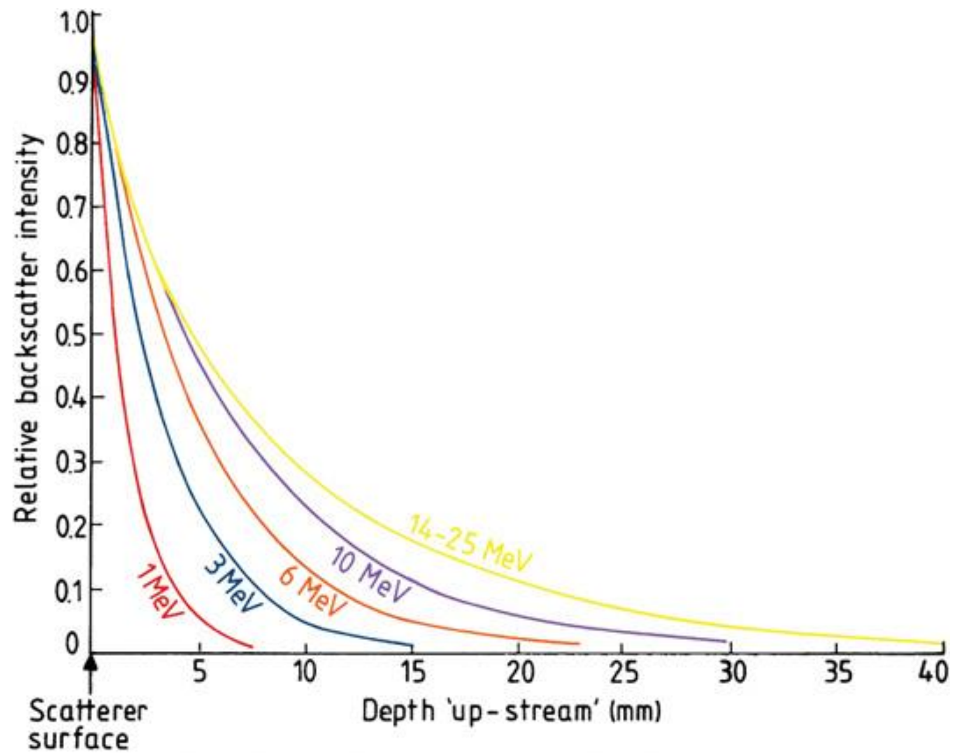
Internal Shielding





Backscatter from Internal Pb shielding

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Internal Shielding

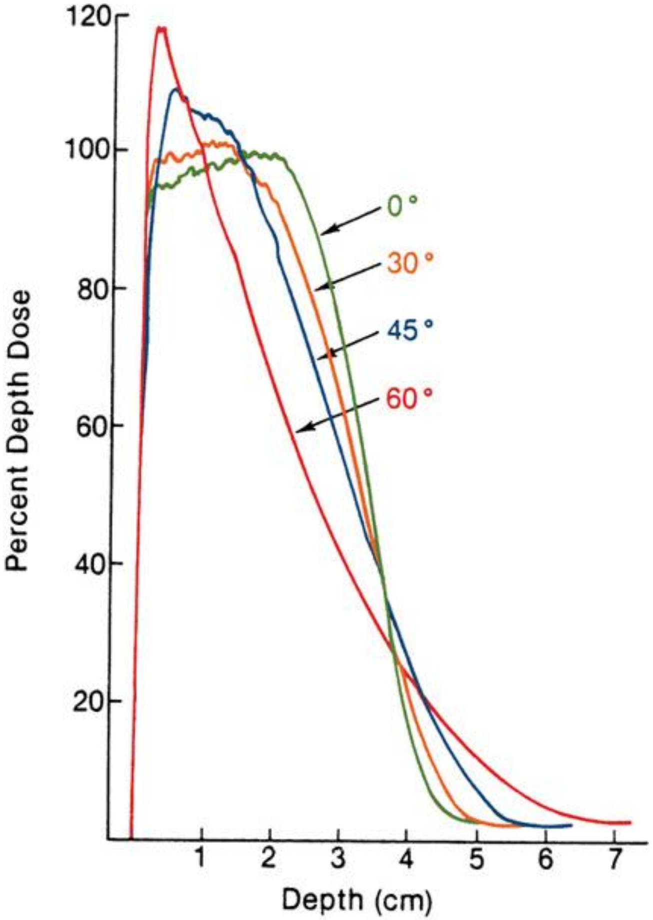
- Electron back scatter Factor (EBF) – The quotient of dose at interface with lead in place to that with homogeneous polystyrene phantom at the same point.

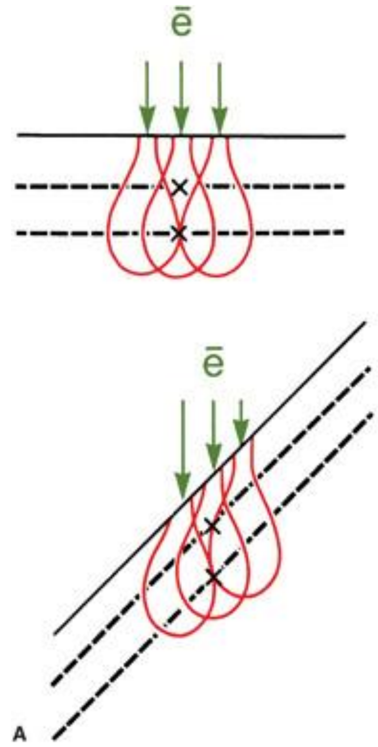
$$EBF = 1 + 0.735e^{(-0.052\overline{E}_z)}$$

Where,

$$\overline{E}_z = \overline{E}_0\left(1 - \frac{z}{R_p}\right)$$

Beam Obliquity





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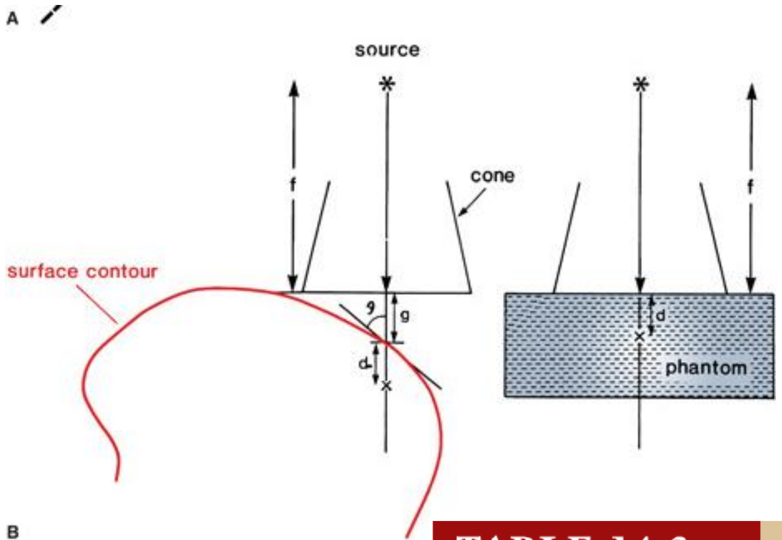
Beam Obliquity



Obliquity Factor = OF(θ,d)

TABLE 14.3 Obliquity Factors for Electron Beams[a]

Z/R_p[b]	E_0 (MeV) 22	18	15	12	9	6
(a) $\theta = 30°$						
0.0	1.00	0.98	0.98	1.00	0.94	1.01
0.1	1.00	1.00	1.00	1.00	1.00	1.08
0.2	1.00	1.00	1.01	1.02	1.05	1.11
0.3	1.01	1.00	1.02	1.03	1.05	1.06
0.4	1.01	1.01	1.02	1.00	1.00	0.96
0.5	1.00	1.00	0.98	0.96	0.92	0.86
0.6	0.95	0.94	0.92	0.90	0.86	0.79
0.7	0.92	0.90	0.87	0.86	0.86	0.83
0.8	0.93	0.85	0.82	0.90	1.00	0.96
0.9	1.09	1.00	1.20	1.11	1.44	1.00
1.0	1.42	1.54	1.50	1.50	1.30	1.00

Monitor Unit Calculation

$$MU = \frac{Rx\ Dose}{\frac{PDD}{100} \times S_e \times EDF \times OF}$$

Rx Dose = Prescribed Dose

PDD = Percentage Depth Dose at Rx Point

S_e =Electron Output Factor

EDF = Extended Distance Factor

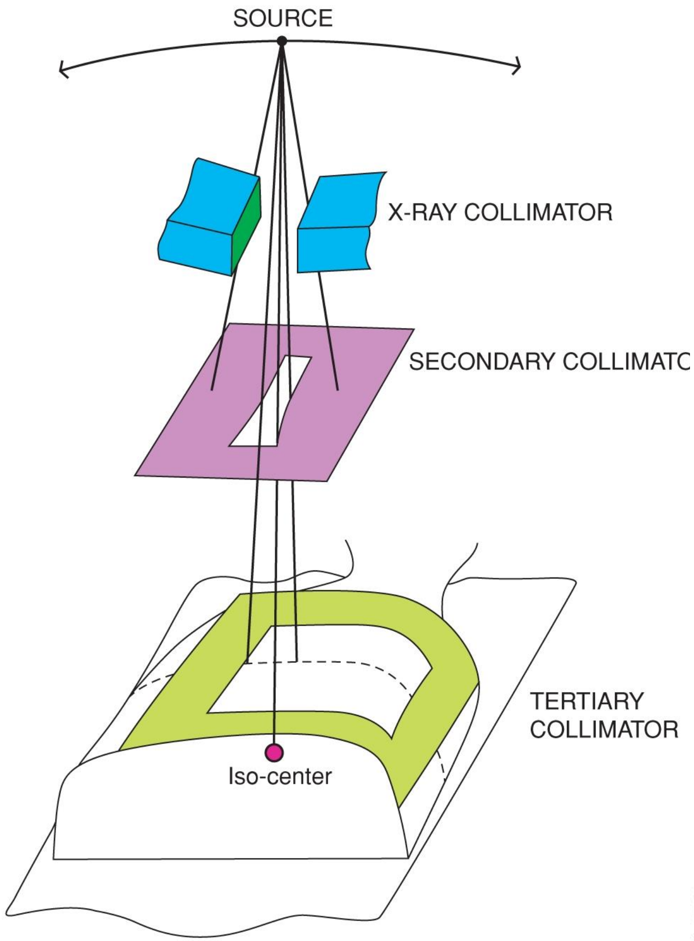
OF = Obliquity Factor

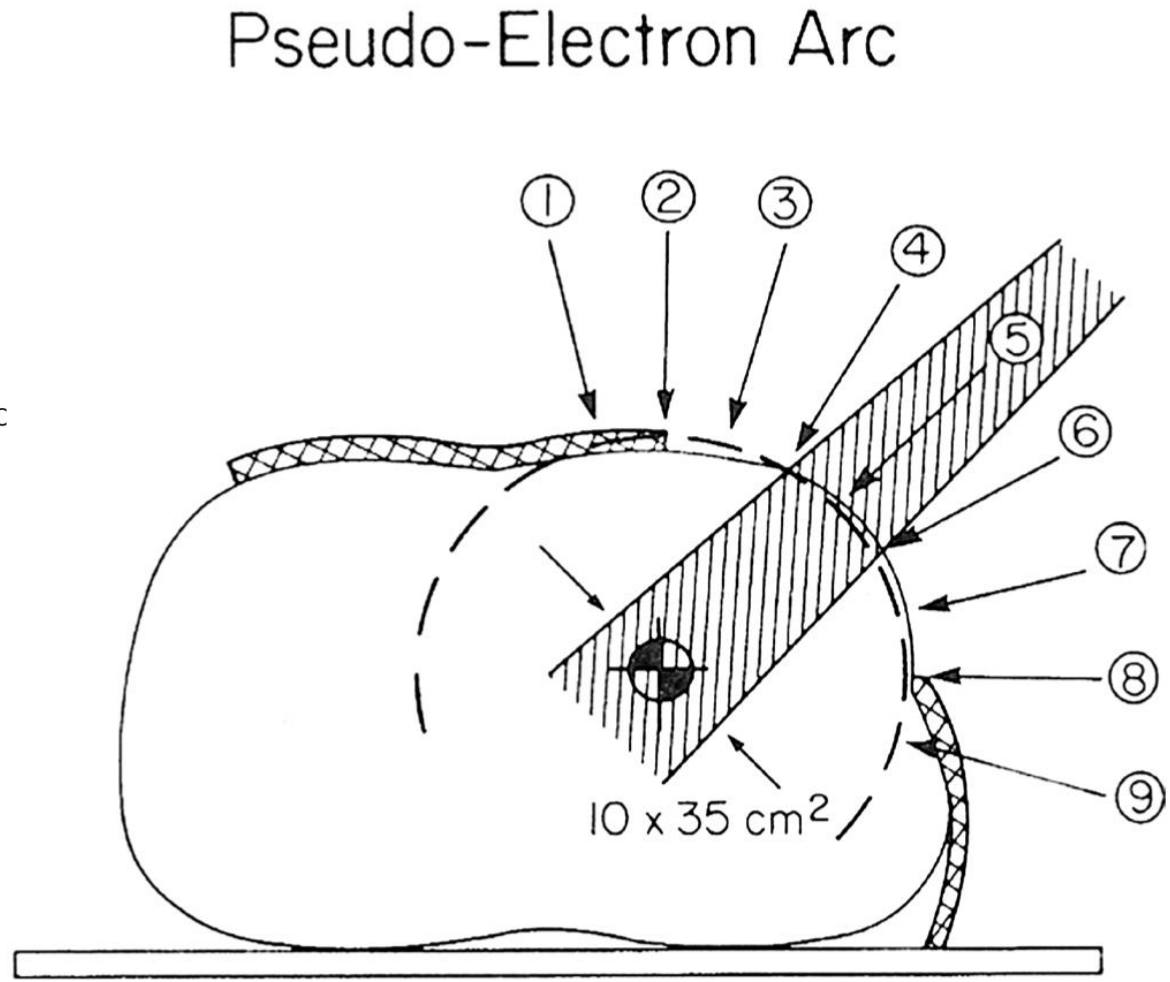
MU Example

- Calculate MU for a 9MeV
- 10x10 cone (S_e=0.01007 Gy/MU)
- Prescribed 2Gy to a depth of 3 cm (PDD = 90%)
- 100cm SSD to surface of 1.0cm bolus

$$MU = \frac{Dose(Gy)}{\left(\frac{PDD}{100}\right) \times S_e} = \frac{2Gy}{(0.9) \times \left(0.01007 \frac{Gy}{MU}\right)} = 221MU$$

Electron Arc





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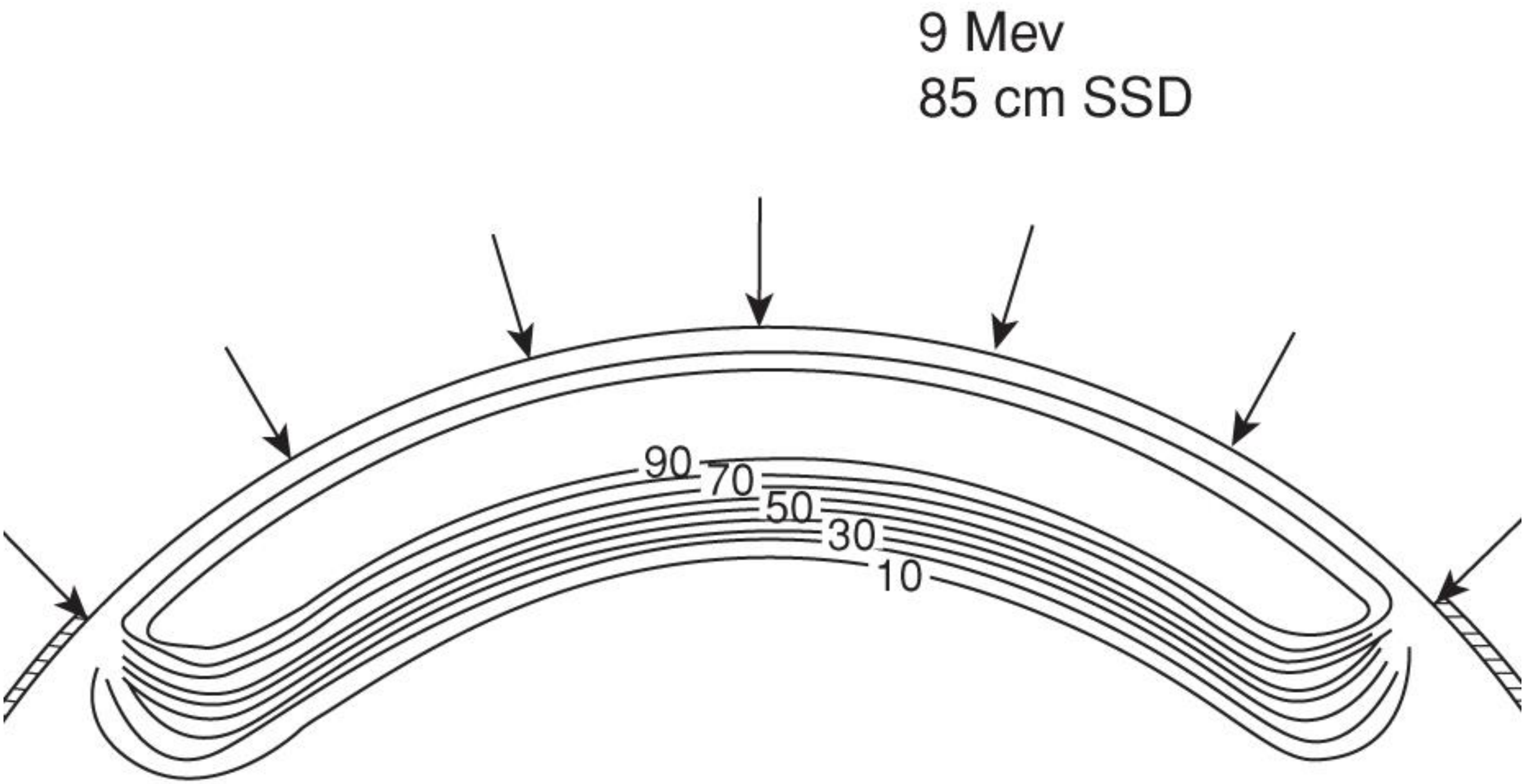
Electron Arc



Proton Therapy

Proton

↓

Ion radical

↓

Free radical

↓

Chemical changes from the breakage of bonds

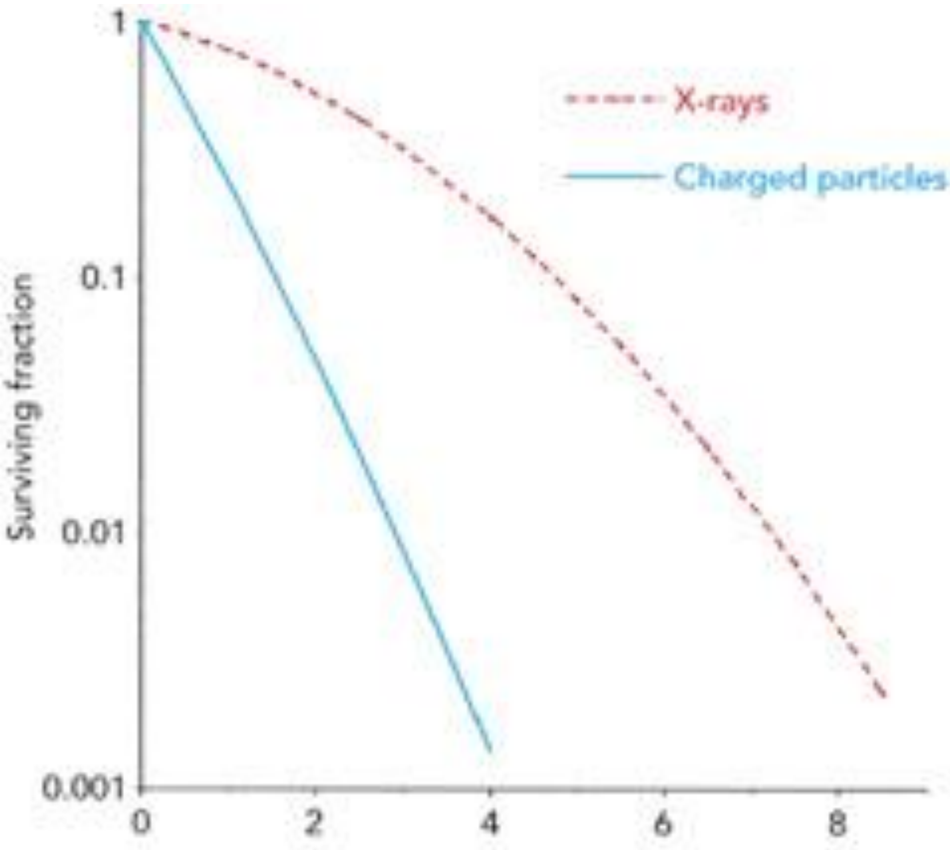
↓

Biological Effects

Proton Interactions

- Inelastic – collisions with atomic electrons
  - Ionization and Excitation of atoms
  - Partial lose of proton kinetic energy
- Inelastic – collisions with nuclei
  - Bremsstrahlung
  - Negligible energy lose
- Inelastic – collisions with nuclei – Head-on
  - excited nucleus, secondary protons, neutrons, α particles, short lived radioisotopes ^{11}C, ^{13}N, and ^{15}O (positron emitters)
  - Rare
- Elastic – collision with nucleus
  - No energy lose
  - Main contributor to multiple Coulomb scattering of protons

Proton Radiobiology



The greater the LET,
the greater is the RBE

Proton dose distributions are biologically equivalent to photon distributions except for a constant RBE factor of 1.1

Example: 49.1 Gy measured proton dose is biologically equivalent to 54 Gy (Co-60) photon dose

Proton Dose distribution therefore stated as:

54Gy (RBE)

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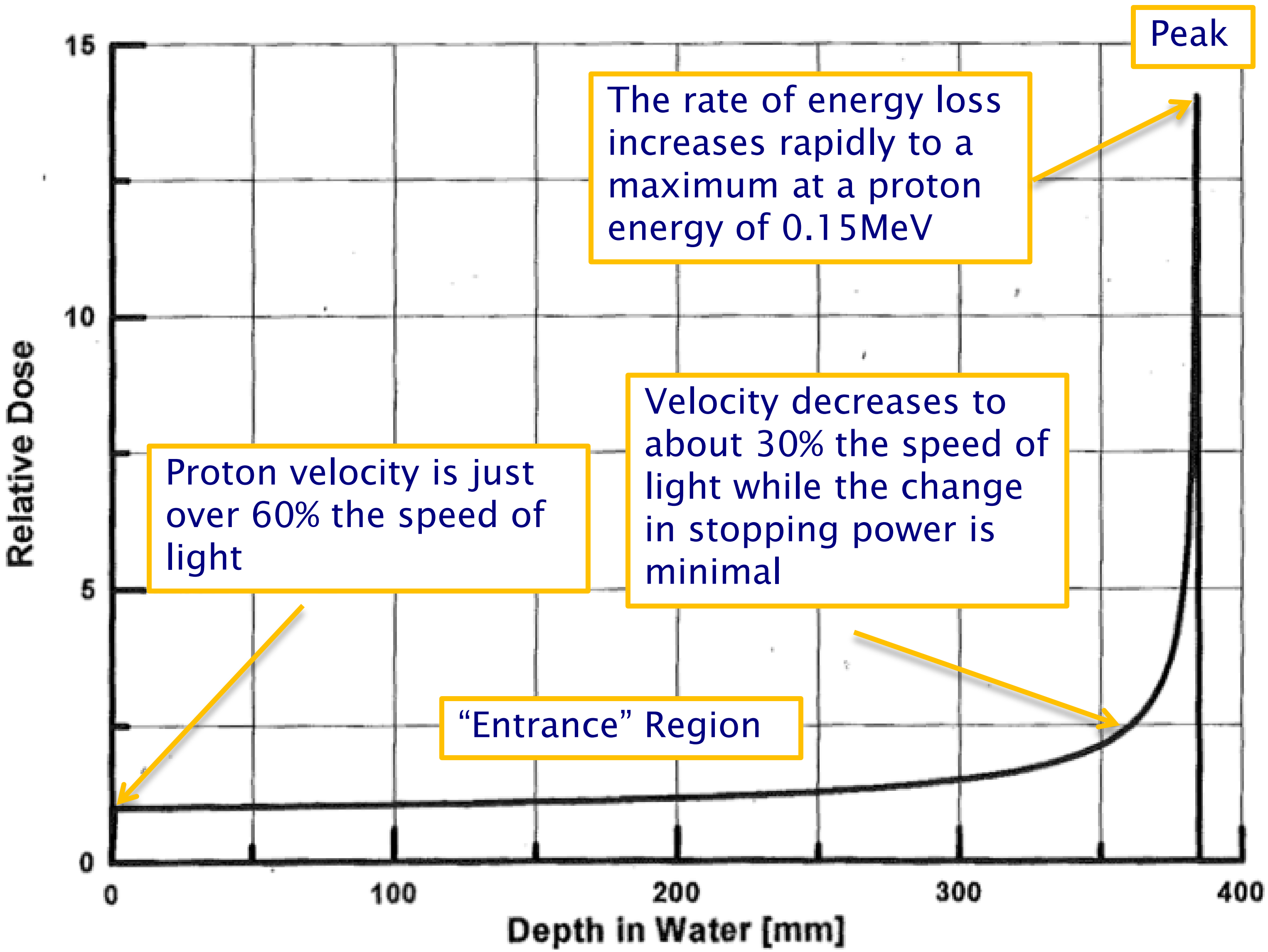
Proton Physics

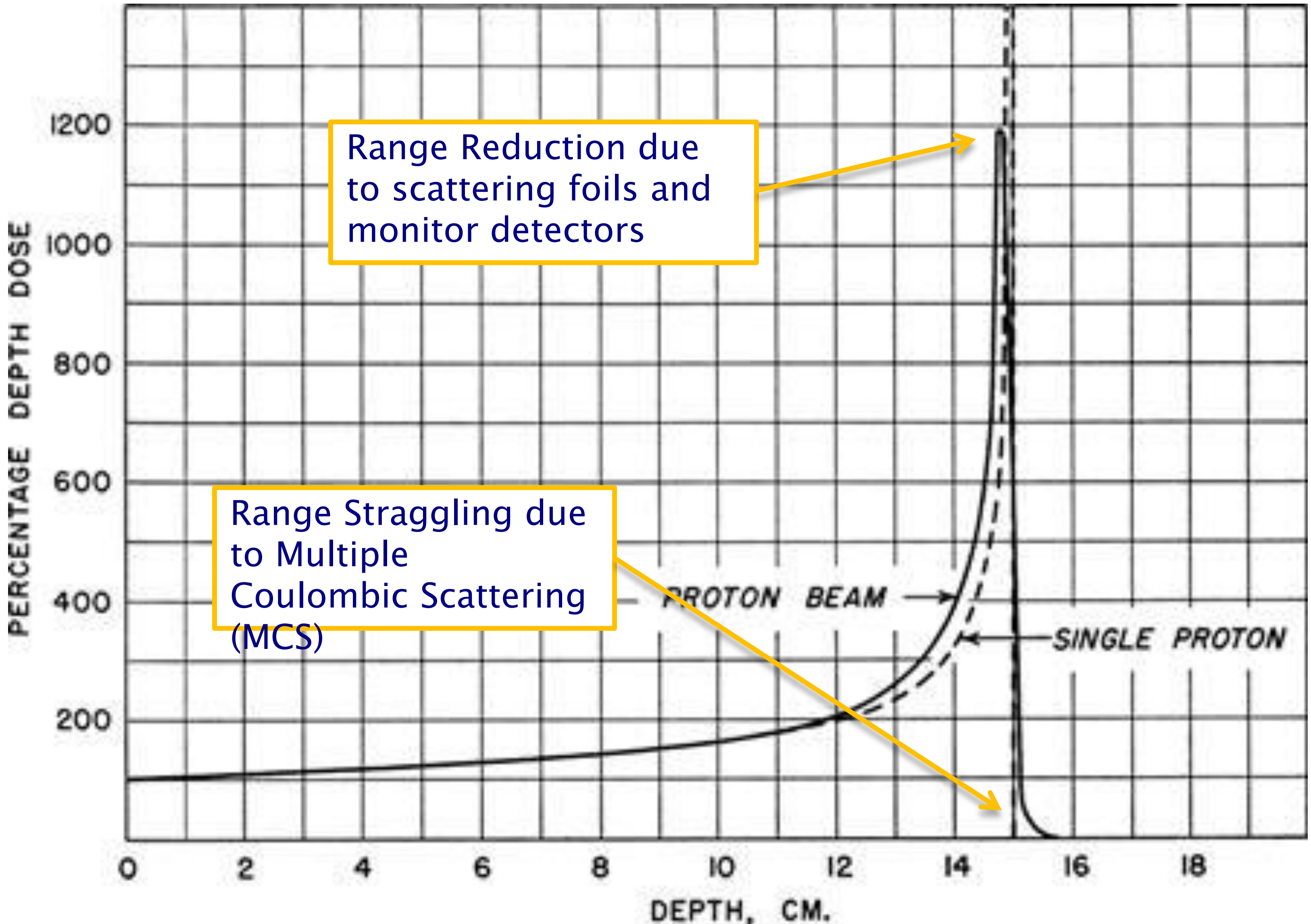
- Mass stopping power (energy loss per unit path length in g/cm^2) for protons is greater in low-atomic-number (Z) materials than in high-Z materials.
  - Low-Z materials are more effective in slowing down protons on a per g/cm^2 basis.
  - Low Z materials are used to decrease proton energy with minimum scattering.
- High-Z materials scatter protons through larger angles than the low-Z materials.
  - High-Z materials are used to scatter a beam with minimum loss of energy (principle of scattering foils).
- Accordingly, through a combination of high-Z and low-Z materials, we can control scattering and reduction in beam energy.

Bragg Peak



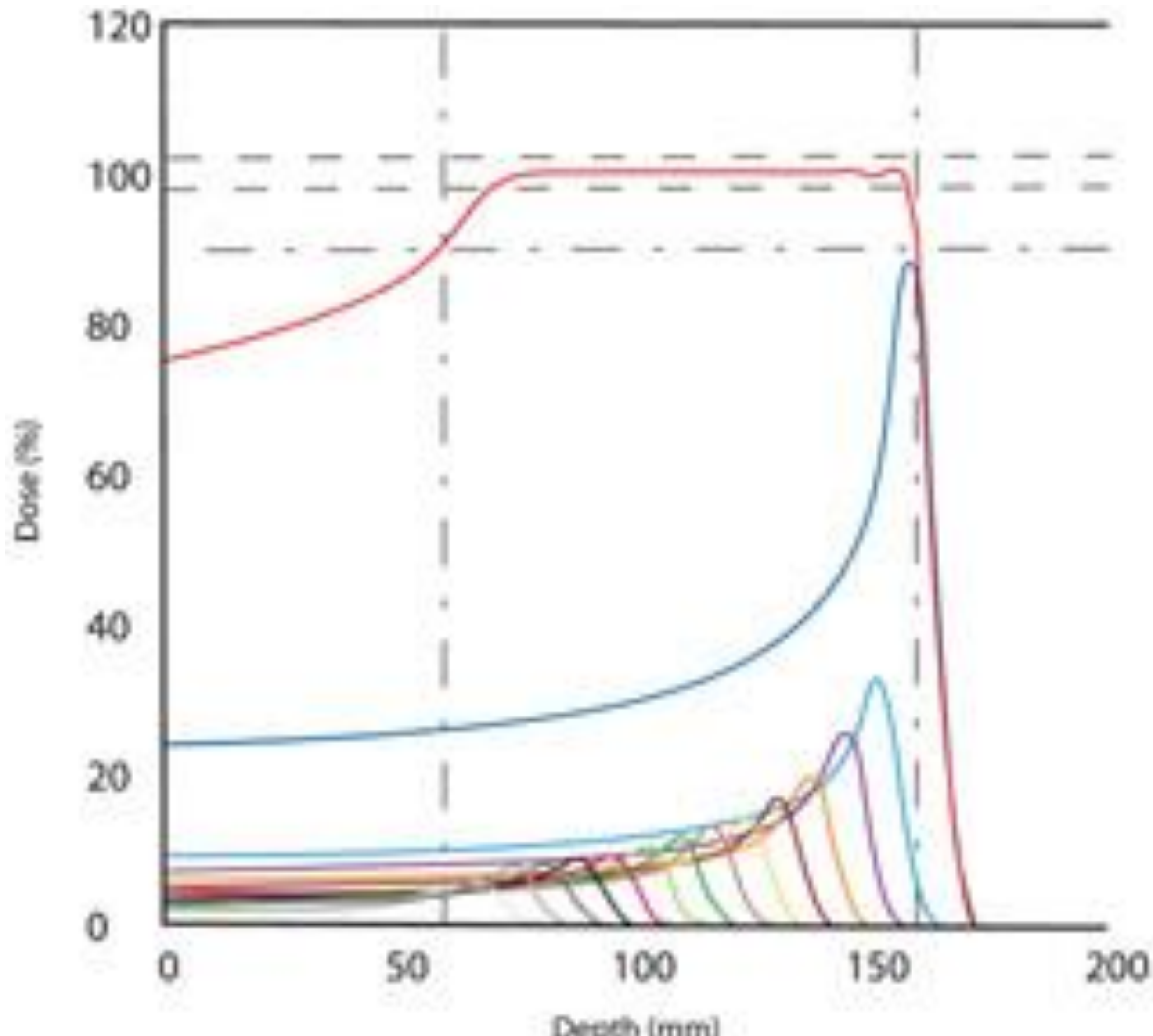
Peak
The rate of energy loss increases rapidly to a maximum at a proton energy of 0.15MeV
Velocity decreases to about 30% the speed of light while the change in stopping power is minimal
Proton velocity is just over 60% the speed of light
"Entrance" Region
Relative Dose
Depth in Water [mm]
0
5
10
15
100
200
300
400

Bragg Peak



Range Reduction due to scattering foils and monitor detectors
Range Straggling due to Multiple Coulombic Scattering (MCS)
PROTON BEAM
SINGLE PROTON
PERCENTAGE DEPTH DOSE
1200
1000
800
600
400
200
0
2
4
6
8
10
12
14
16
18
DEPTH, CM.

Spread Out Bragg Peak



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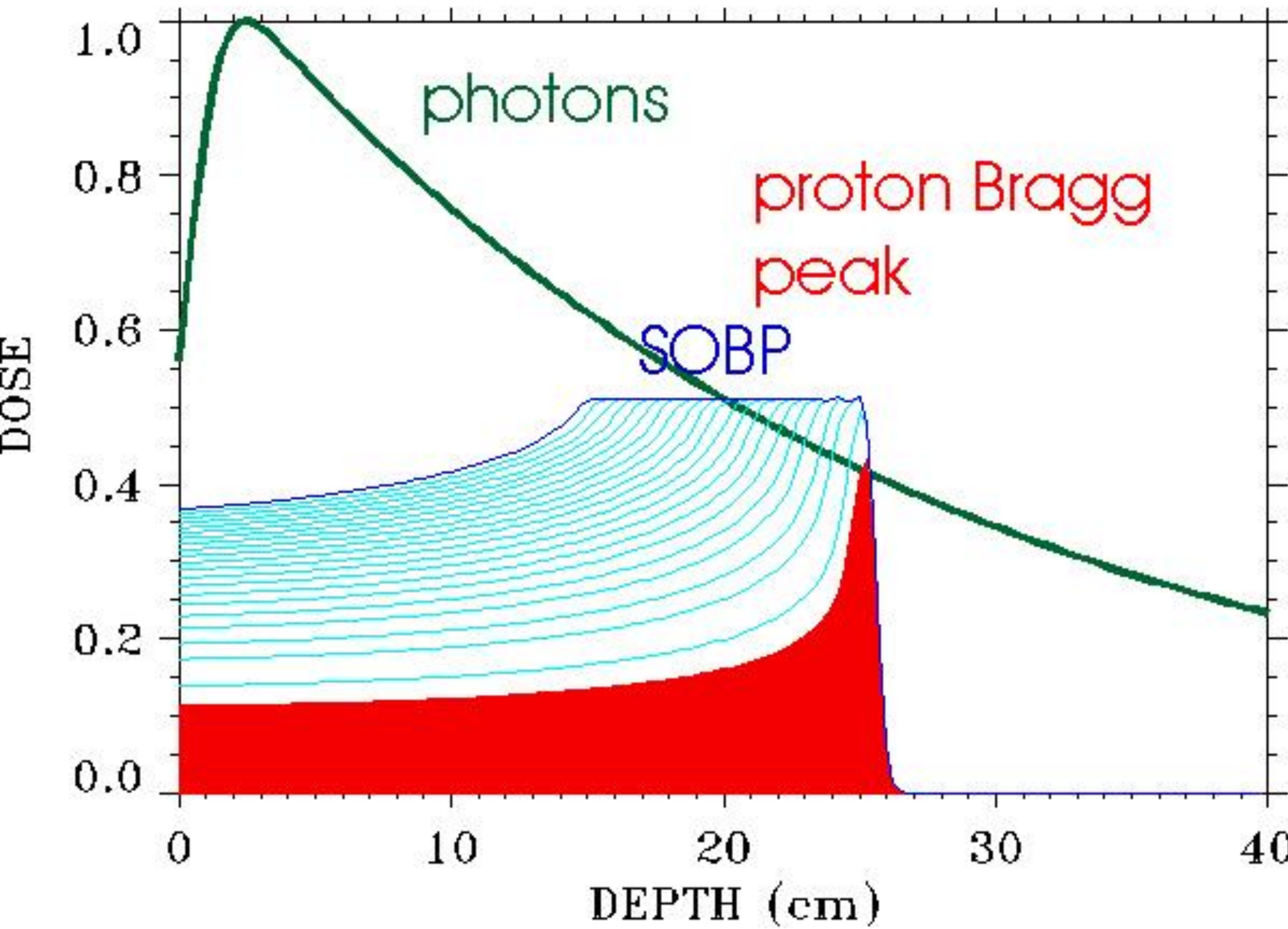
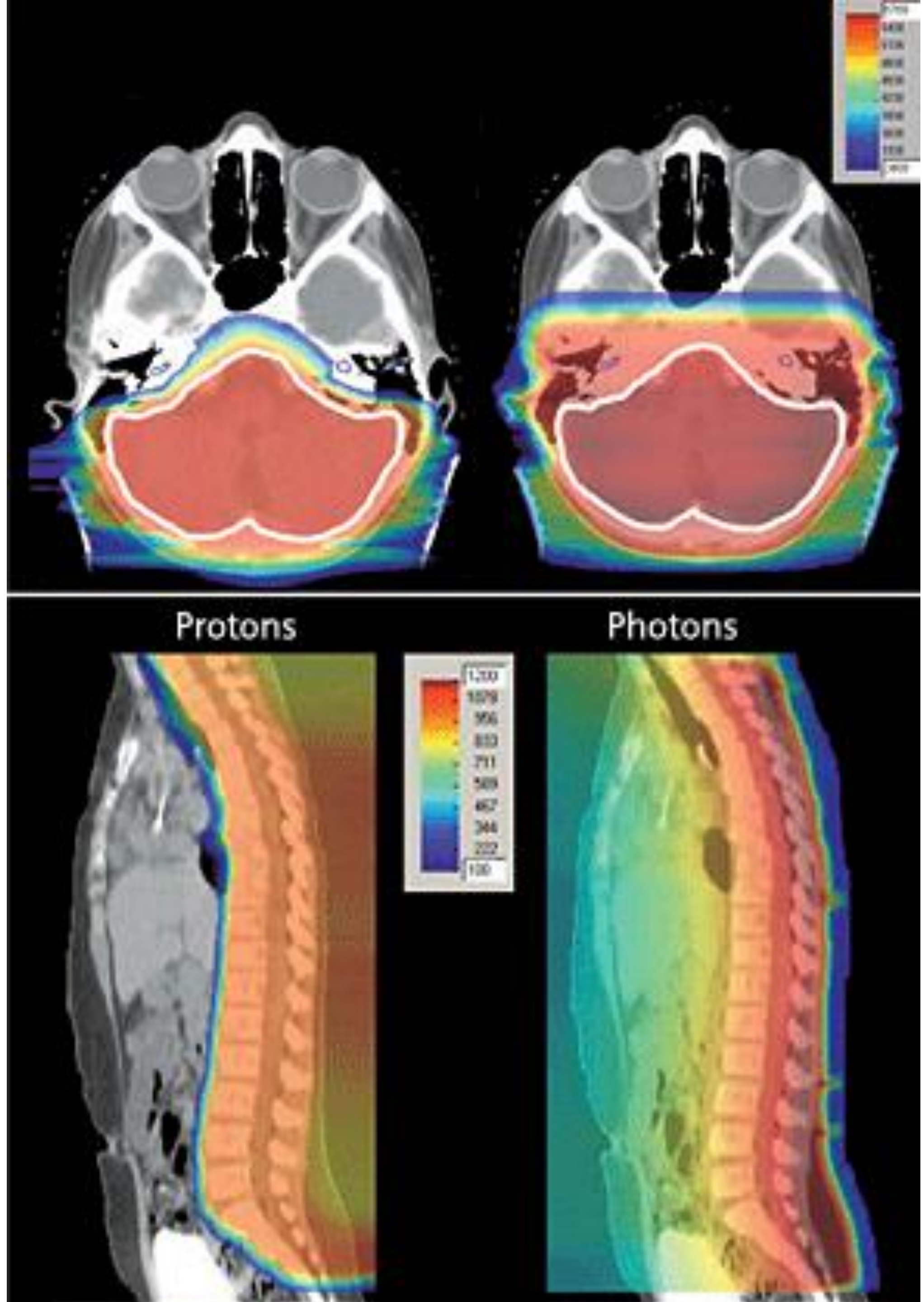
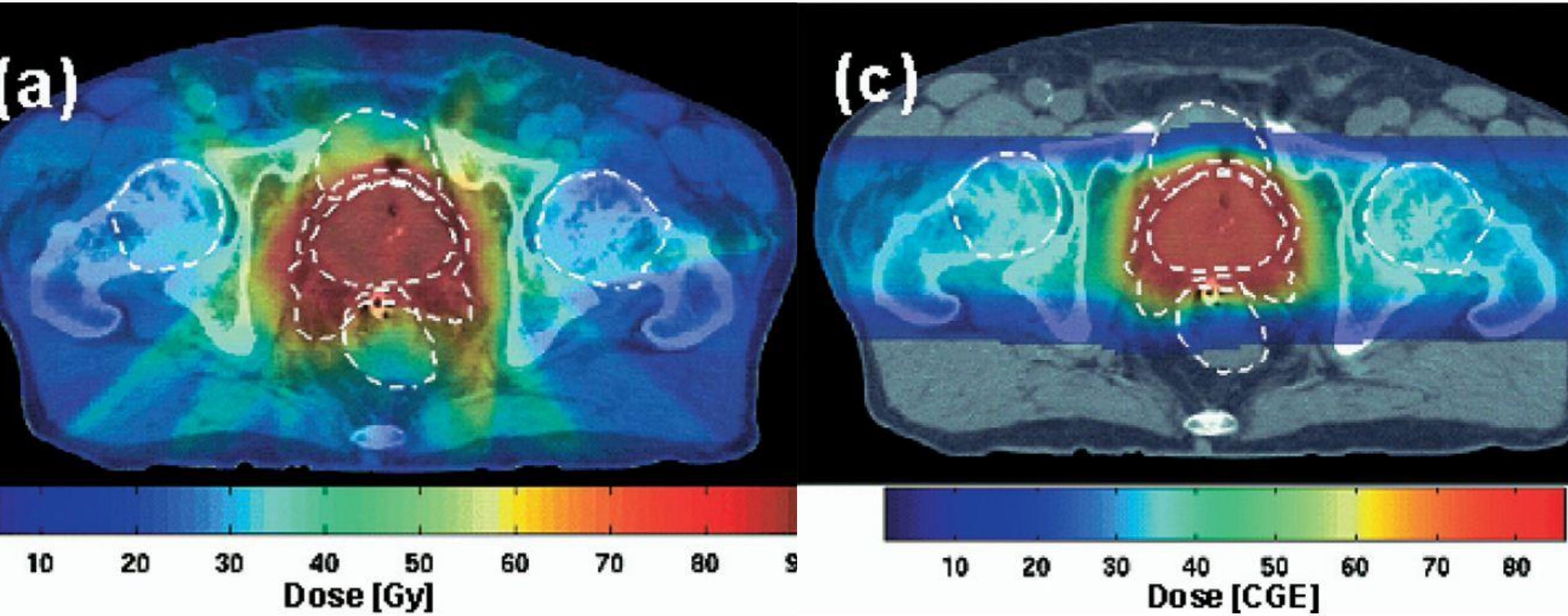


photons
proton Bragg
peak
SOBP
DOSE
DEPTH (cm)
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40

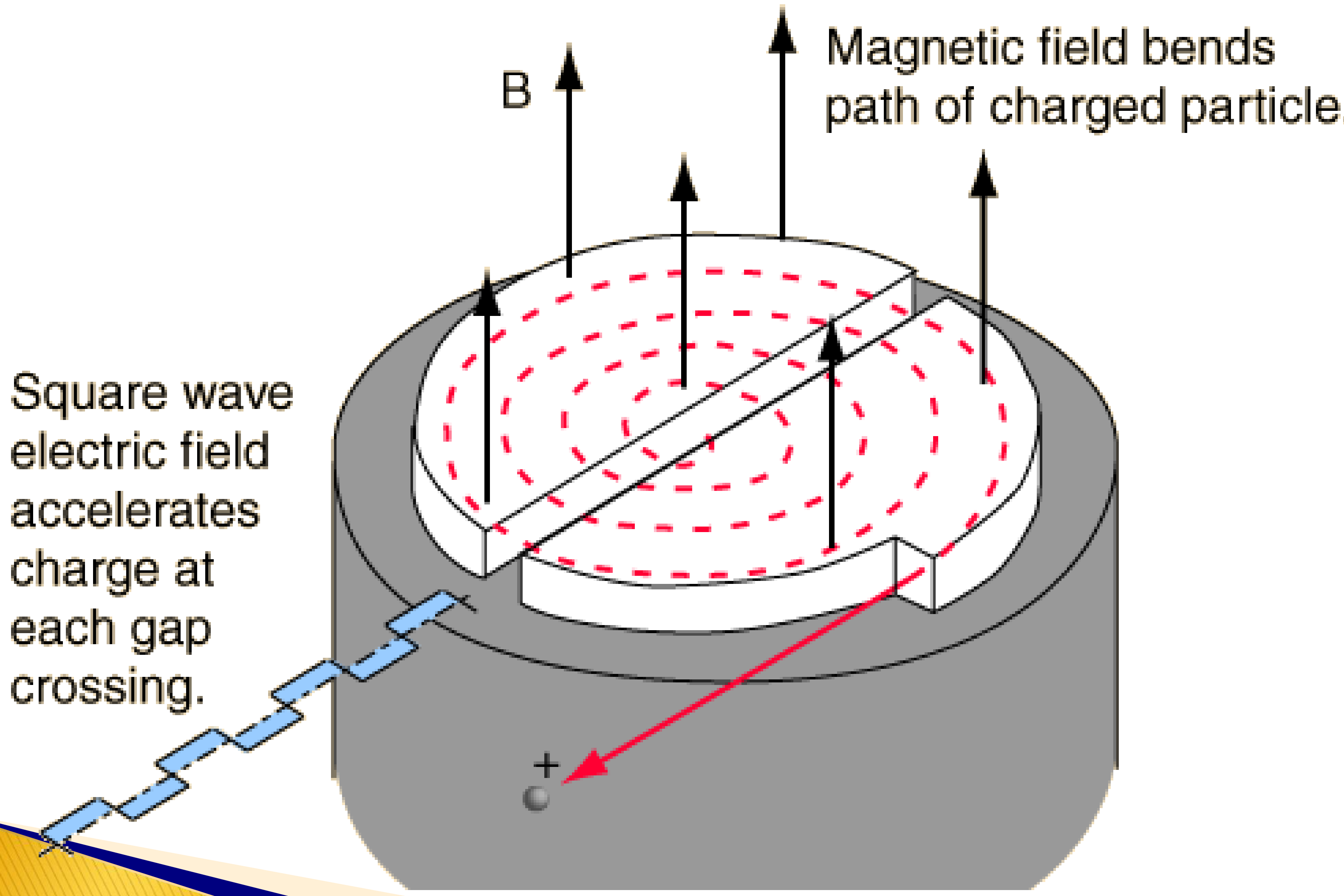
CNS Proton vs Photon



Prostate
Photon vs. Proton

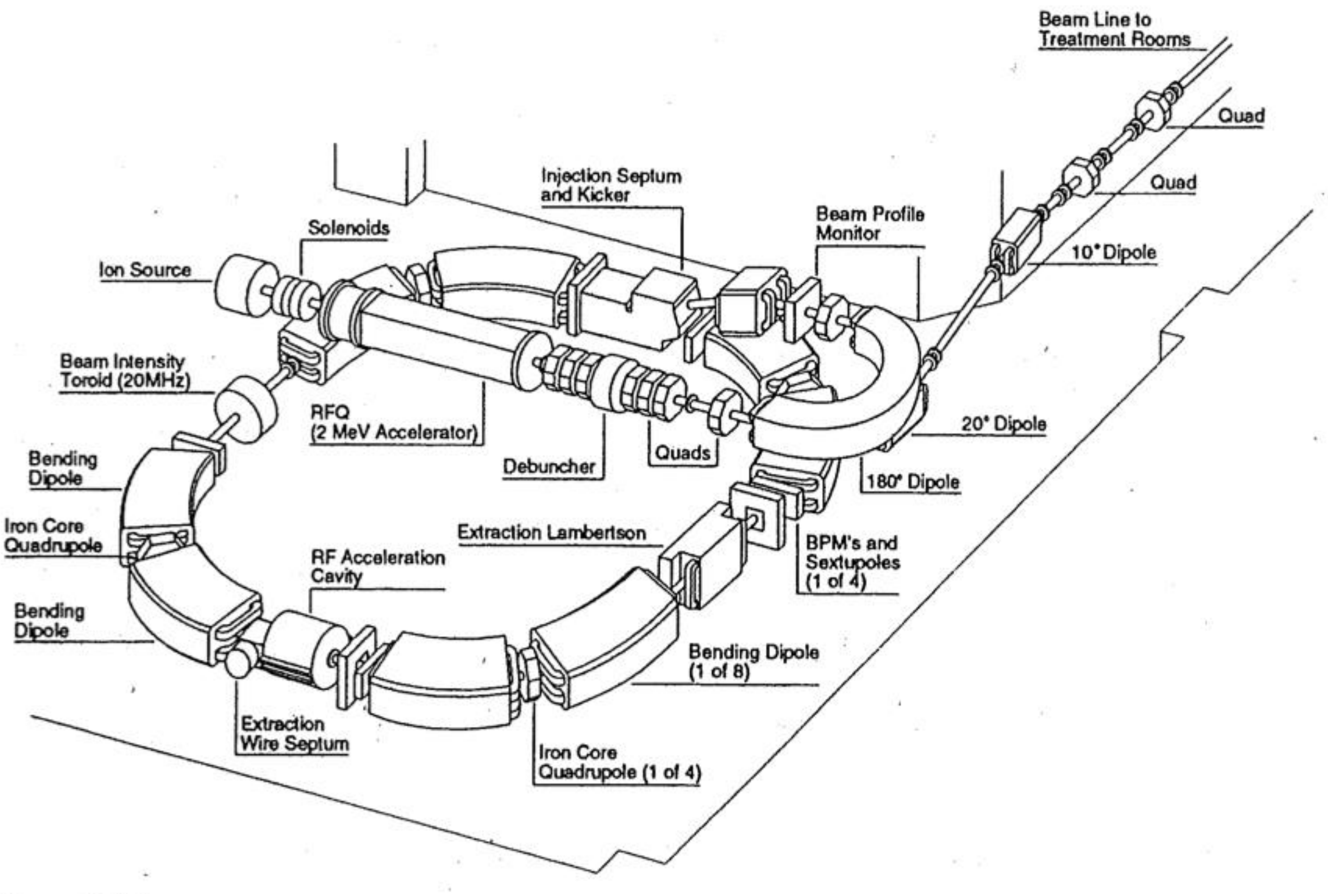


Proton Beam Delivery Techniques
Cyclotron

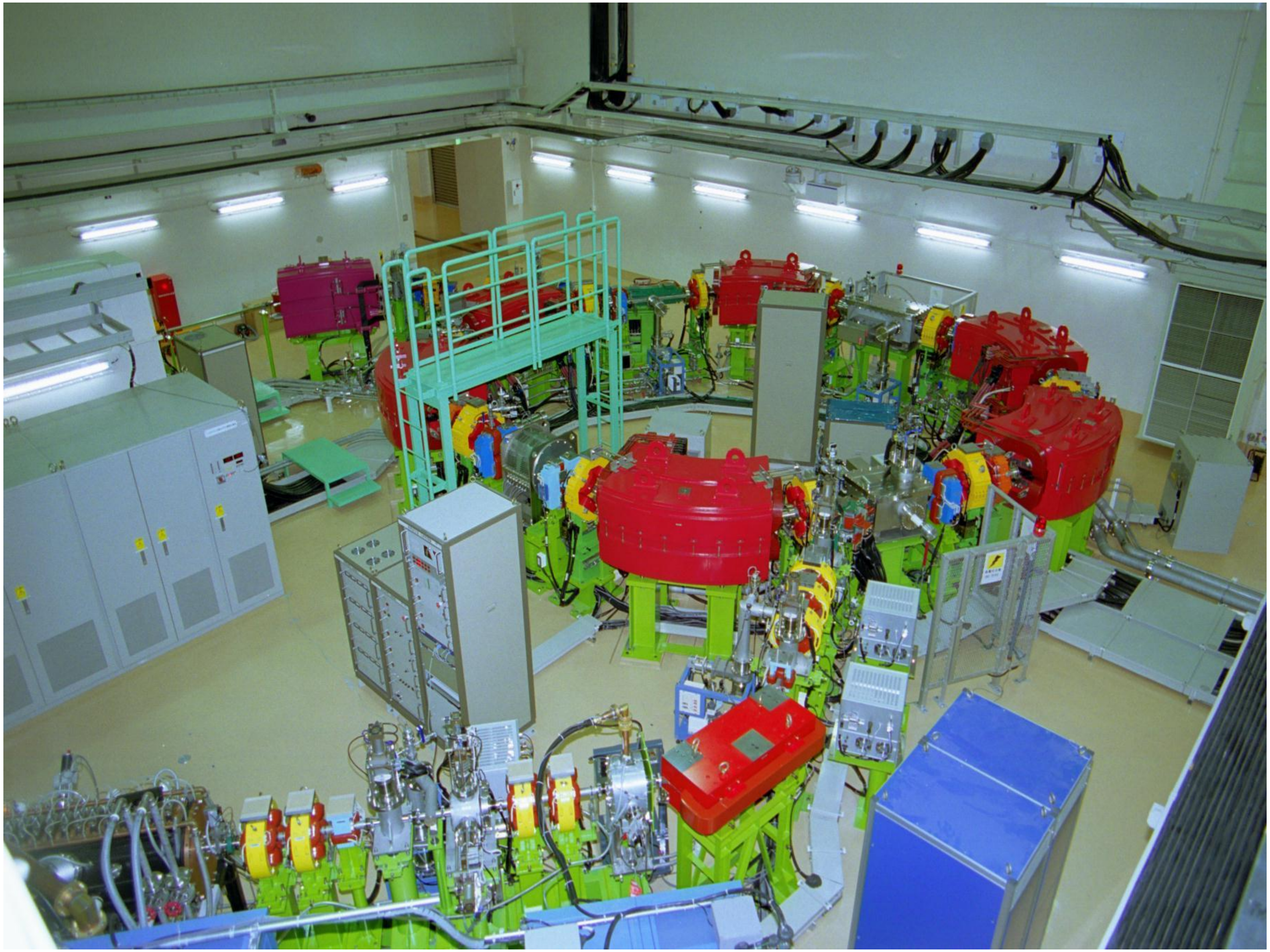


Proton Beam Delivery Techniques
Cyclotron

Proton Beam Delivery Techniques
Syncrotron



Proton Beam Delivery Techniques
Syncrotron



Proton Beam Delivery Techniques

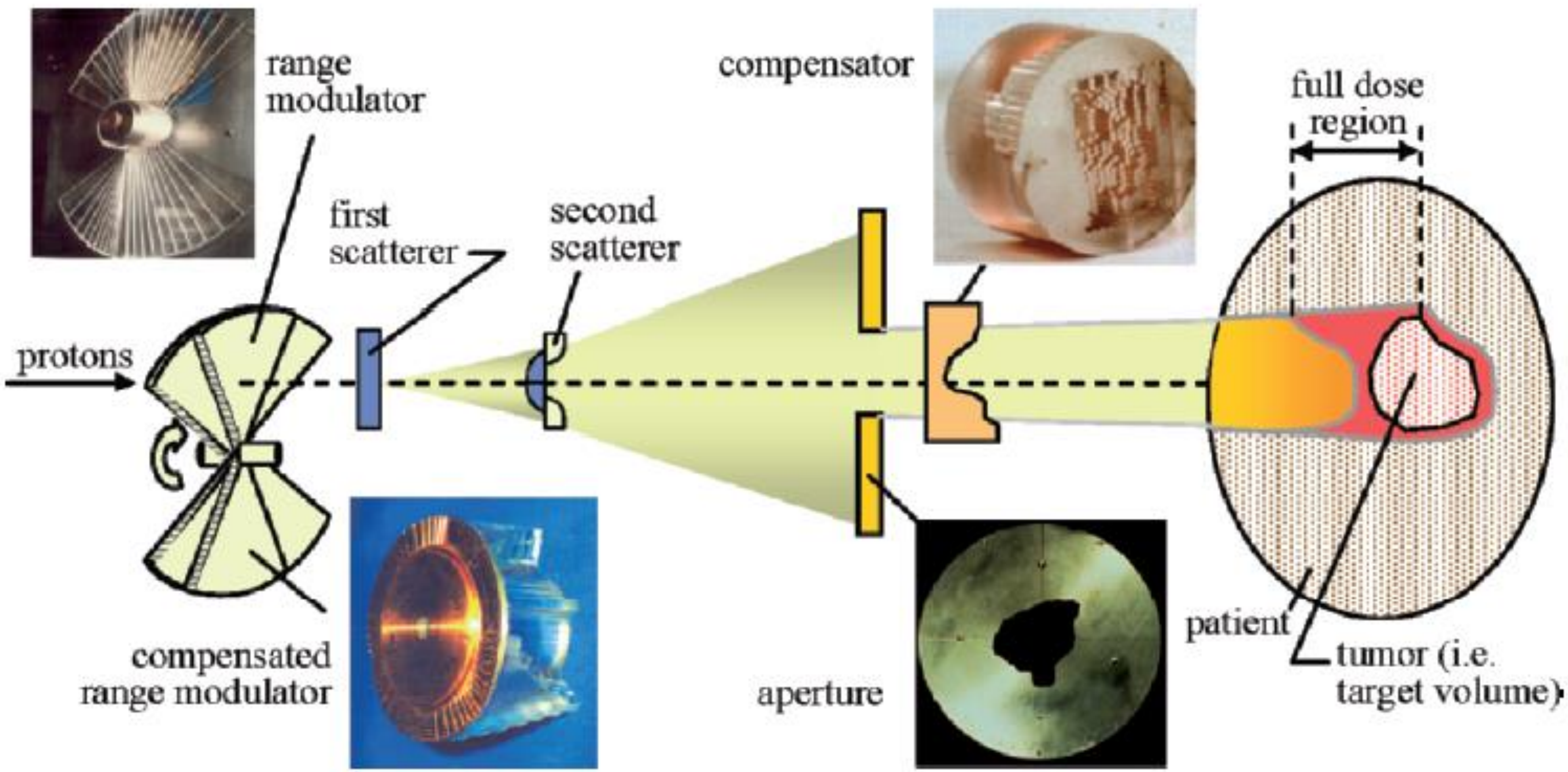
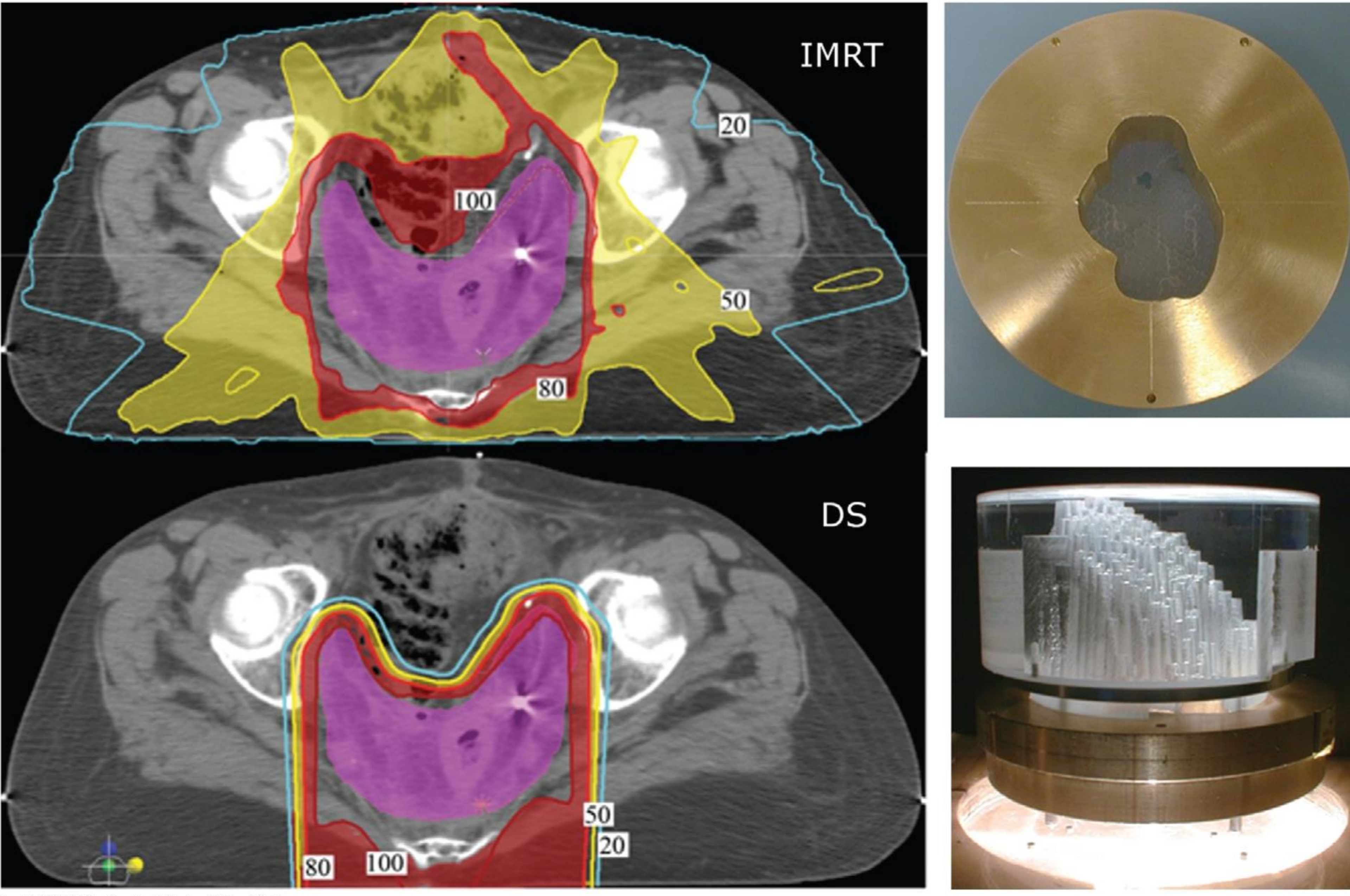


Figure 10.19. Schematic diagram, not to scale, of a passive scattering nozzle (see text). *N.B.* monitoring devices are omitted in this diagram.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Proton Beam Delivery Techniques

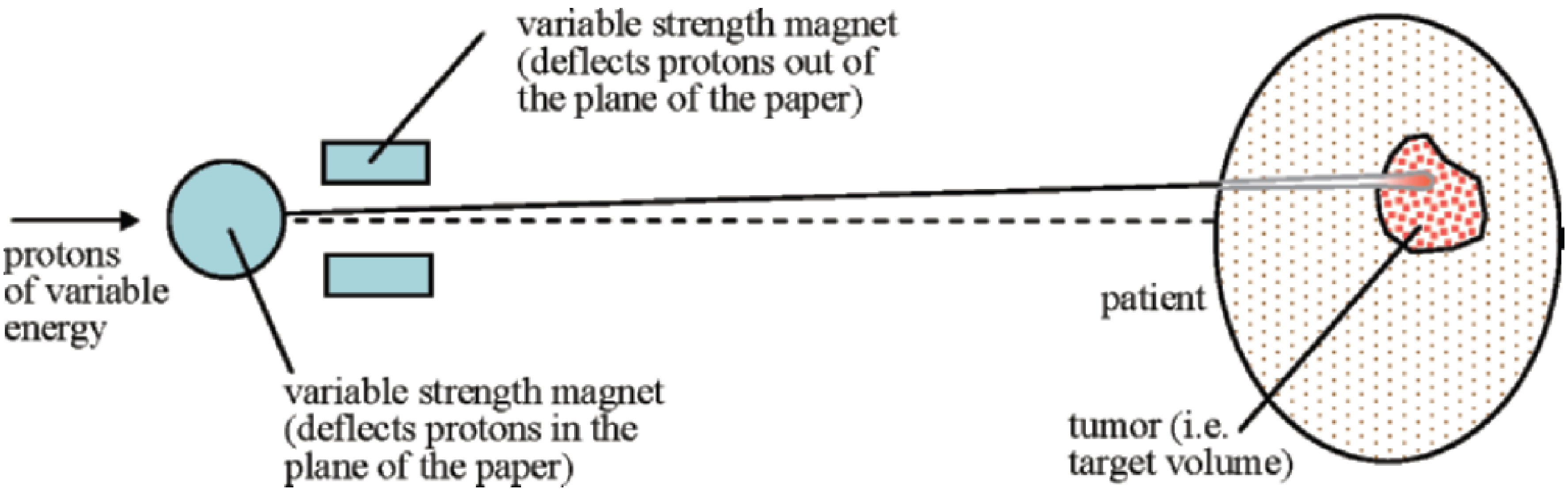
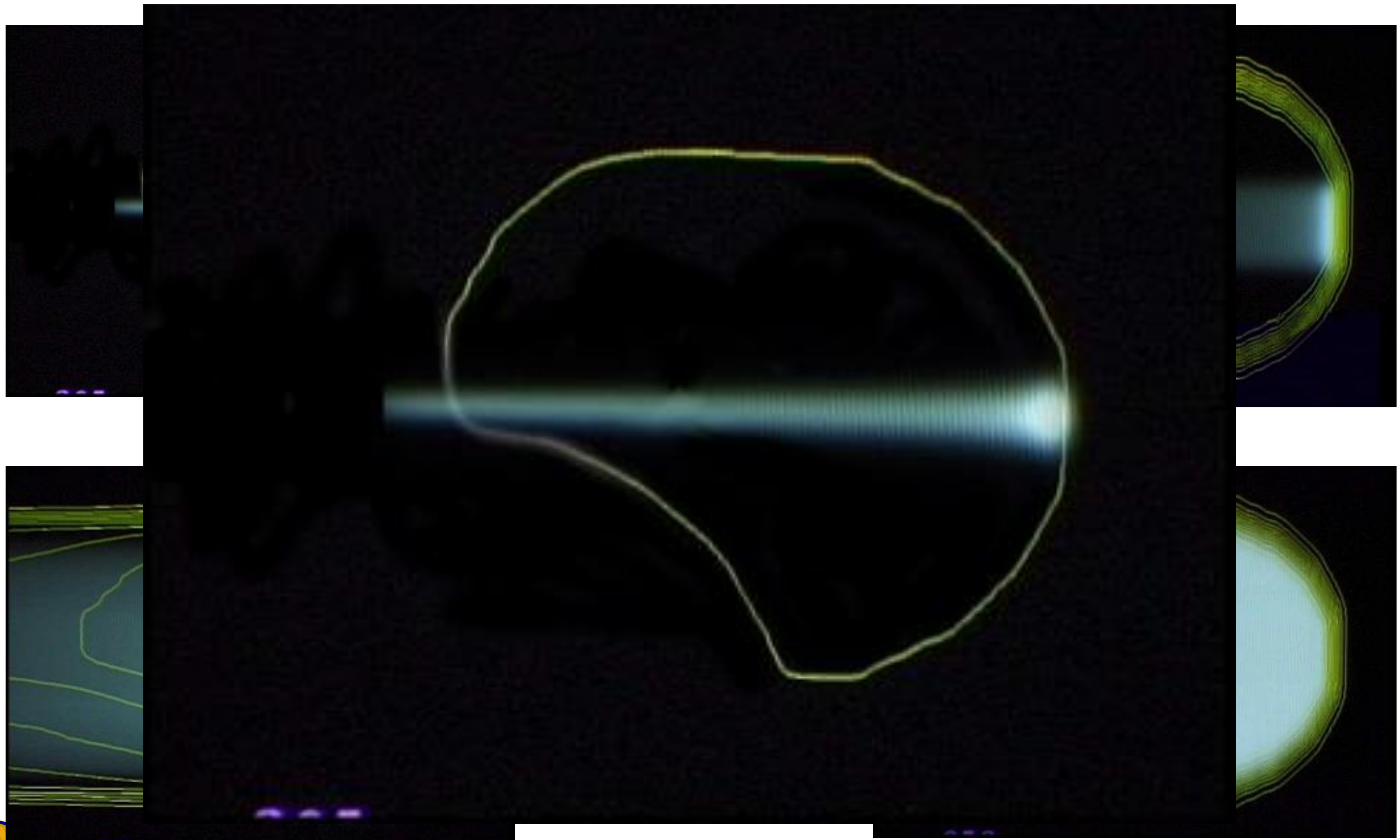


Figure 10.21. The basic elements of a scanning nozzle (see text). *N.B.* monitoring devices are omitted in this diagram.

Scanning Beam



Effects of Inhomogeneities

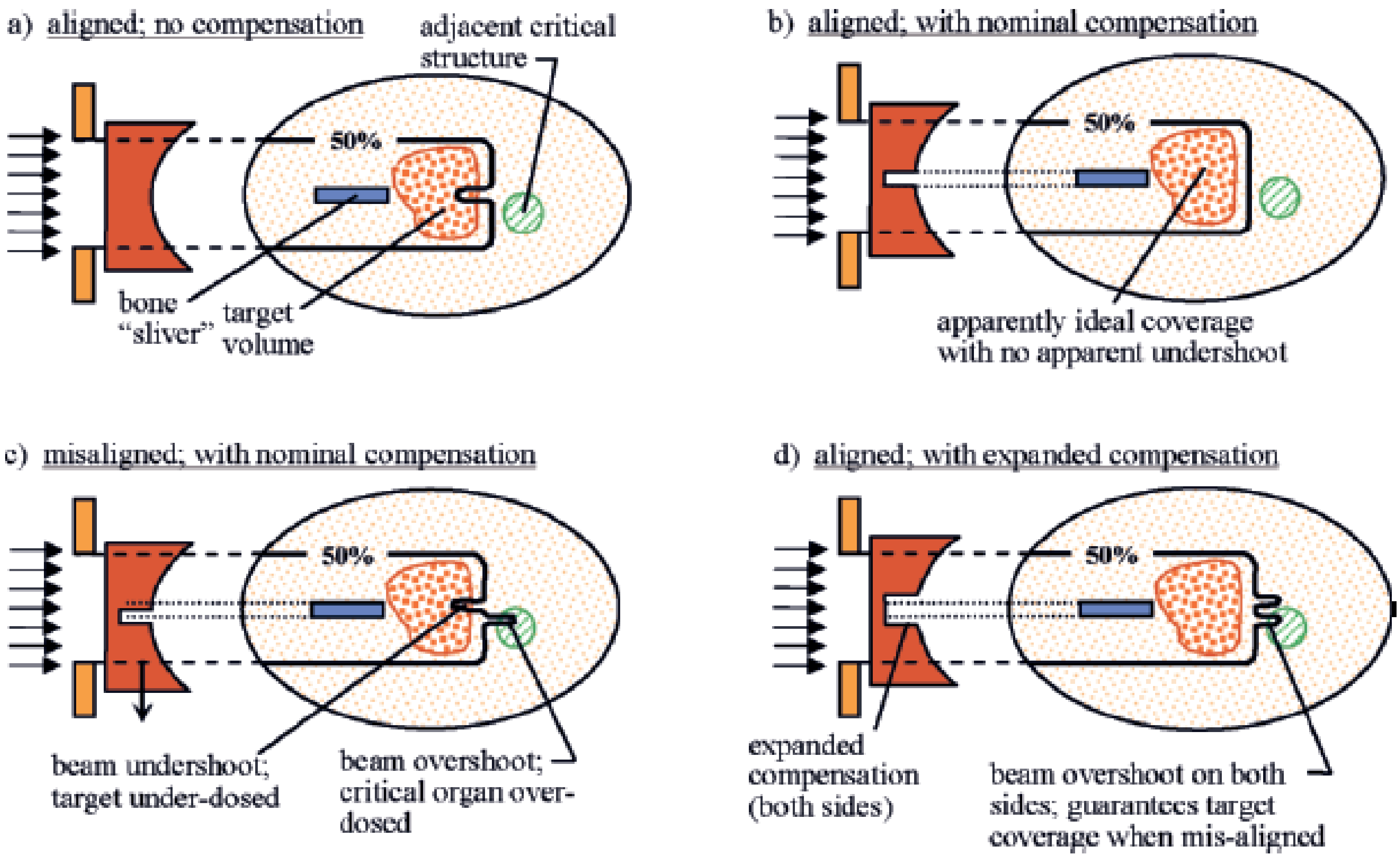
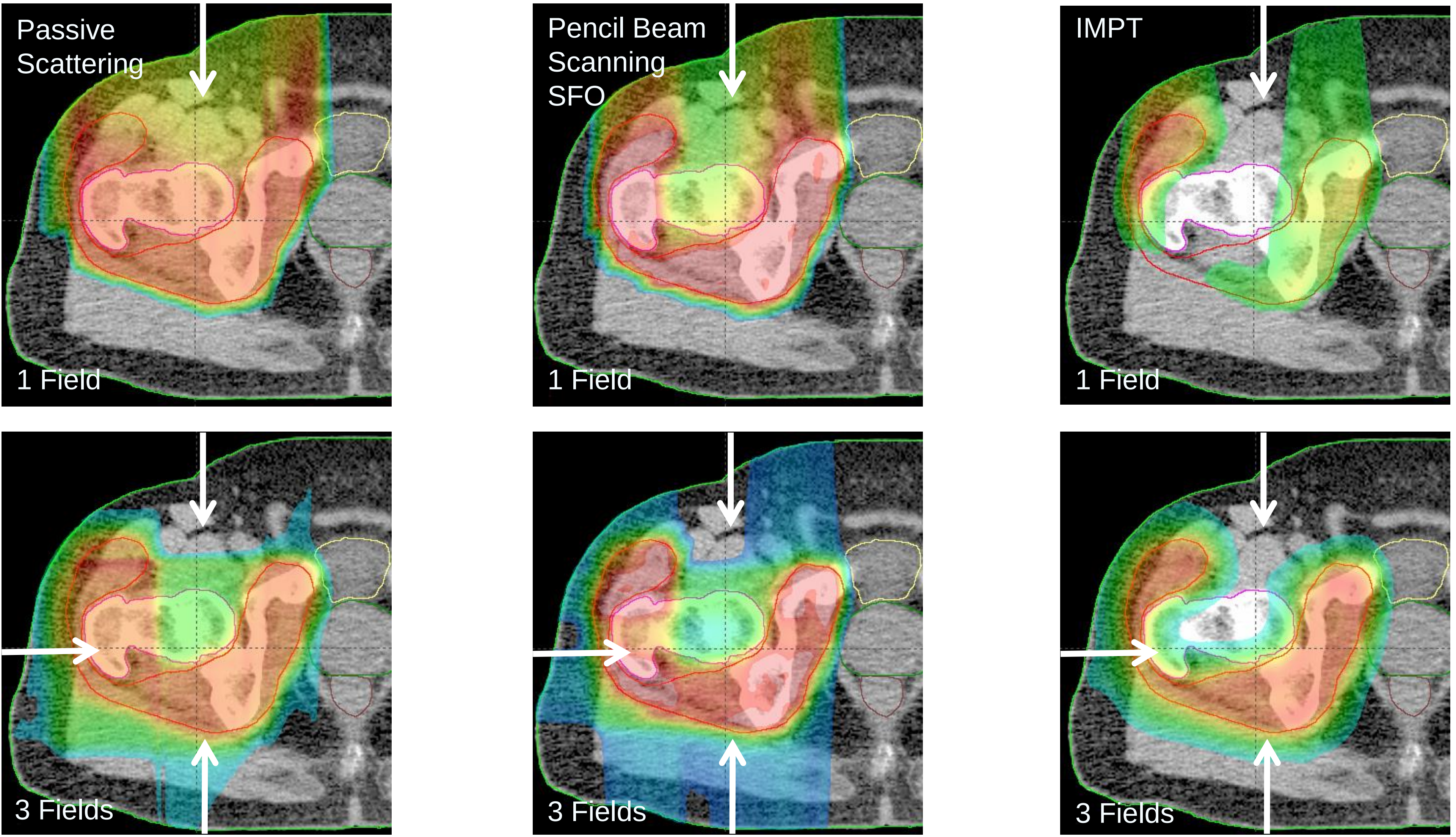


Figure 11.7. Schematic representation of the design of a compensator

Comparison of Proton Techniques



Acknowledgements and References

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