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Photon & Electron Interactions

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Topics

- Interactions of Electromagnetic Radiation with Matter
- Interactions of Particulate Radiation with Matter
- Characteristics of Photon Beams
- Quantification and Measurement of Dose (including SI units)

Interactions of Electromagnetic Radiation with Matter

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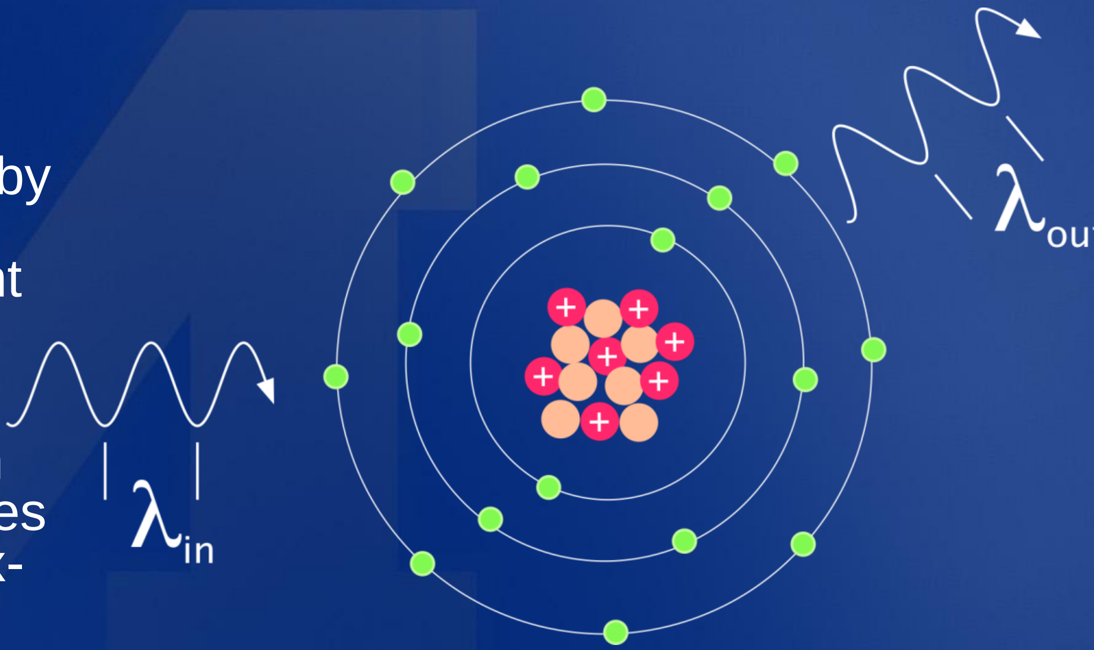
- Coherent
- Photoelectric
- Compton
- Pair
- Photodisintegration

Coherent (Rayleigh) Scattering

- Low-energy photon interacts with entire atom and produces a slight excitation, causing all electrons in atom to oscillate.
- Electrons then radiate energy by emitting a photon of the same energy but in a slightly different direction → no net transfer of energy.
- Typically a small effect (5%) in diagnostic radiology, contributes small amount to scatter in an x-ray image.



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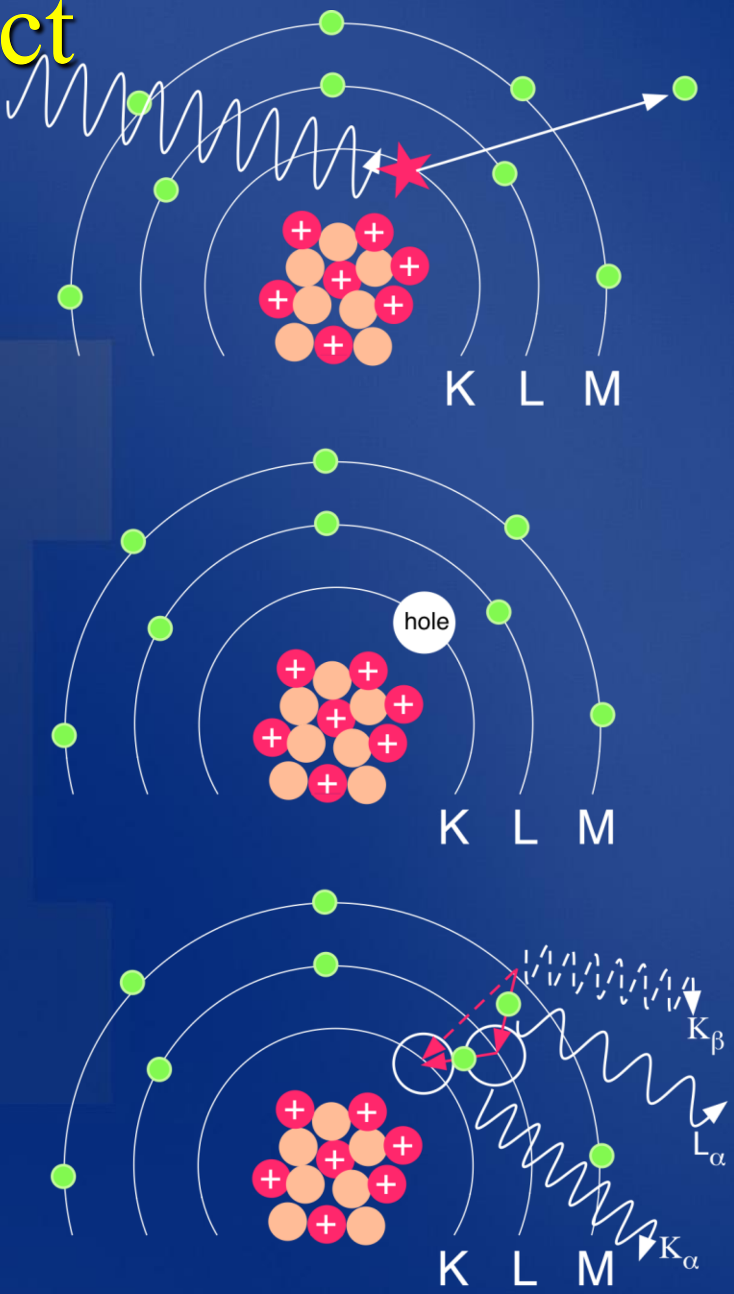
Photoelectric Effect

- Incident photon complete transfers all of its energy to an atomic electron.
- Electron ejected from atom with

$$E_e = E_o - E_B.$$

- Vacancy created by ejected electron filled by electrons from higher lying shells.
- Results in a cascade of characteristic x-rays.

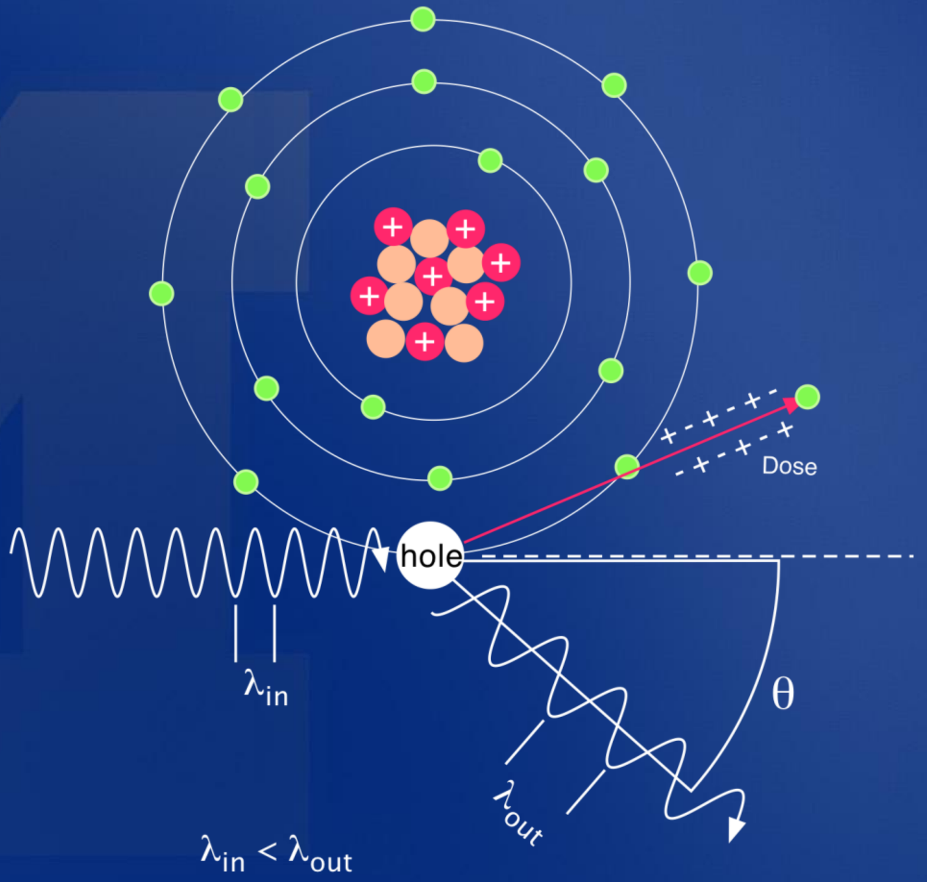


Photoelectric Effect (Cont.)

- For any photon of energy greater than the K-binding energy of the absorber, photoelectric effects takes place predominately in the K shell, L shell contributes ~ 20% and outer shells even less.
- Probability of photoelectric effect proportional to Z^3/E^3.
- Attenuation is dependent on Z of absorbing material. Higher the Z, the greater the attenuation.

Compton Scattering

- Incident photon interacts with loosely bound atomic electron.
- Results in:
  - Scattered photon, whose energy is less than incident photon and in a new direction.
  - Compton scattered electron that was ejected from atom with transferred energy minus binding energy.



Compton Scattered Photon

- Incident photon can be scattered up to ±180º with respect to its original direction.
  - If photon scattered back in the direction of its initial approach ($\phi = 180^o$), it has "backscattered."
  - As angle of deflection decreases, energy retained by scattered photon increases.

$$h\nu' = h\nu[1+\alpha(1 - \cos\phi)]^{-1}$$

or

$$\Delta\lambda = (0.00243 \text{ nm})(1 - \cos\phi)$$

where $\alpha = h\nu/511$ keV.

Compton Electron

- Compton interactions most commonly happen with outer-shell electrons, low binding energy.
- Ejection of a Compton electron is in a direction $\pm$ 90^o with respect to incident photon.

$$E_k = h\,\nu - h\,\nu' - E_B$$

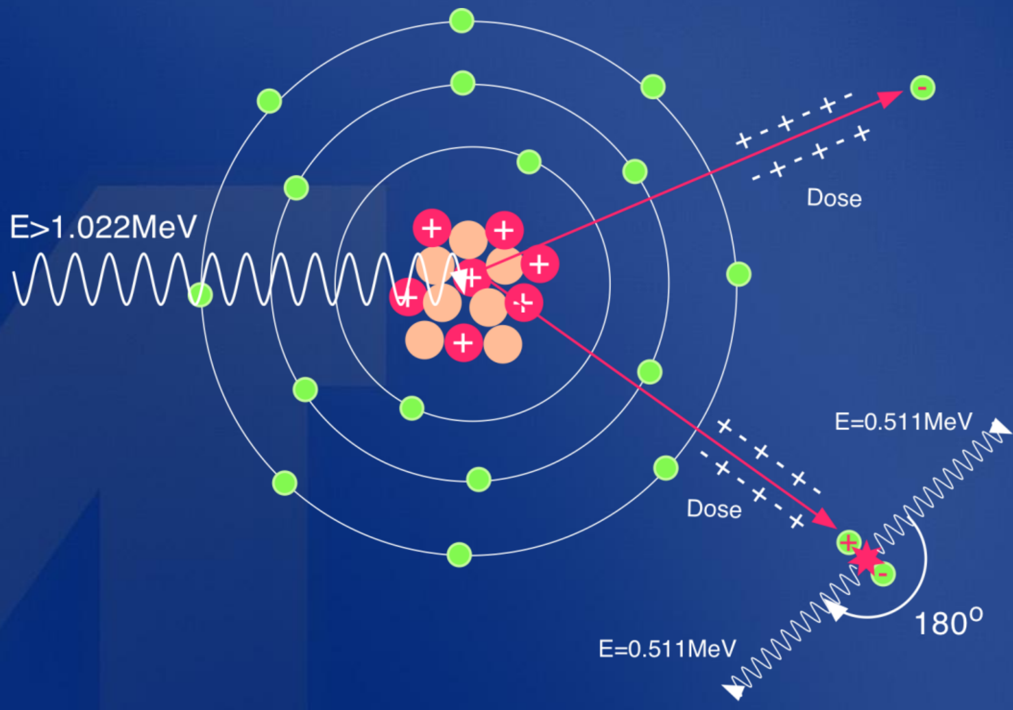
  - E_B is almost always negligible.
- Energy transferred to electron is maximized when photon is backscattered.

Probability of Compton Scattering

- Predominate interaction at photon energies ranging from 30 keV and 30 MeV.
- Proportional to number of outer-shell electrons in absorbing medium $\rightarrow$ electron density.
- Slowly decreases with photon energy.
- Independent of Z.
- Number of Compton interactions (attenuation) dependent on Z/A. For the most part, attenuation is independent of absorbing material because:
  - For most substances, $Z/A \sim 0.5$.
  - Exception, hydrogen, $Z/A = 1$.

Pair Production

- As incident photon passes near nucleus, it spontaneously transforms into an electron (e^-) and positron (e^+).
  - Threshold energy 1.02 MeV (2 x rest mass of an electron).
- Electron will gradually slow down and be absorbed by the medium.



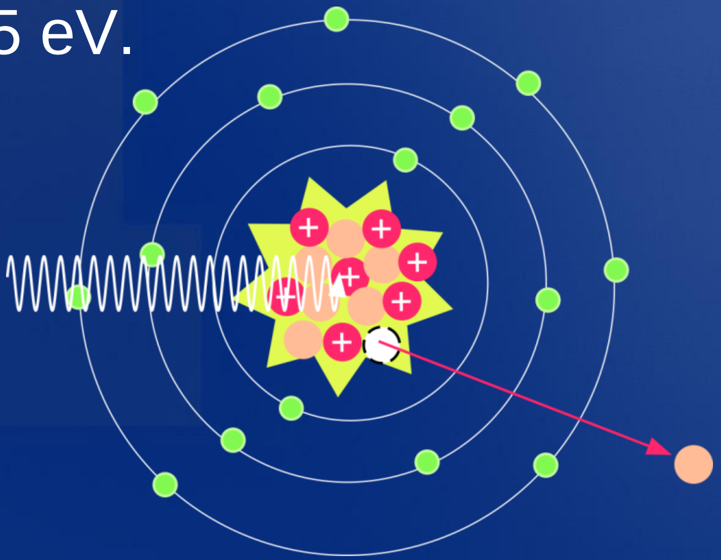
- Positron will also slow down, however, since it is an unstable particle it will interact with an electron and annihilate, producing two 511 photons emitted 180° apart.

Pair Production (Cont.)

- If E_o > 1.02 MeV, excess energy distributed to the positron and electron → does not have to be equally divided.
- Pair production is not relevant in diagnostic radiology and is only of interest when using high energy photon beams (> 10 MeV).
- Probability of PP $\propto$ Z*E

Photodisintegration

- When E_o > 10 MeV it is possible for photon to interact (totally absorbed) by nucleus and emission of one or more nucleons.
- In most cases, this results in emission of neutron.
  - – Slow/thermal neutrons – E < 0.5 eV.
  - – Fast neutrons – E > 0.5 eV

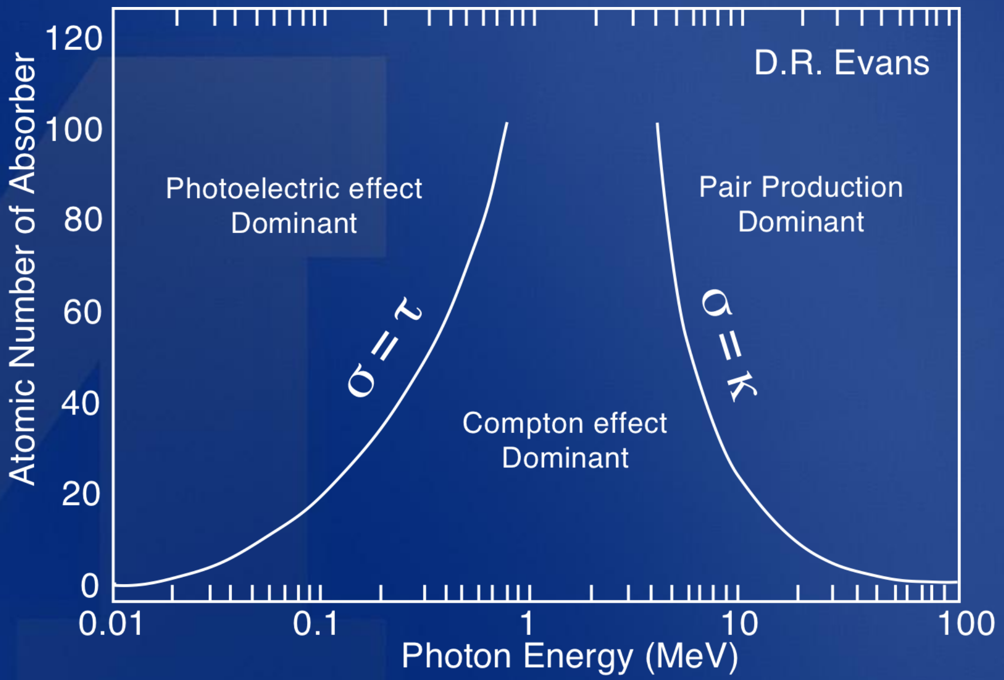


Photodisintegration

- Special precautions need to be taken to for therapy rooms operating at x-ray energies greater than 10 MeV to stop neutrons that are produced → paraffin and lead lined doors.
  - Paraffin is a material with a high concentration of hydrogen. Hydrogen has roughly the same mass as a neutron, effectively moderates neutrons.
  - As neutrons slows down, energy released in the form of photons, which are then attenuated by Pb.

All Together Now

- Photon interactions in the diagnostic and therapeutic energy range:
  - Coherent scattering
  - Photoelectric effect
  - Compton scattering
  - Pair production
  - Photodisintegration
- The three photon interactions of interest in tissue for therapy are PE, Compton and PP.
- Probability of photon interaction:
  - PE $\propto$ Z/E
  - Compton $\propto \rho_{e-}$
    - Slowly ↓ as E ↑.
  - PP $\propto$ Z*E



Linear Attenuation Coefficient

- μ is the fraction of incident photons that are attenuated (removed from the beam) per unit distance (SI units 1/m).
  - Dependent on the energy of incident photons and composition of medium (Z and density).

Mean Free Path

- Average distance photons travels before they interacts with medium.
  - MFP = $1/\mu$ = 1.44 HVL

Attenuation of Photons

- Under narrow-beam geometry, the number of monoenergetic (same energy) photons transmitted through a given material of thickness x exponentially decreases with increasing thickness as:
- $I = I_o e^{-\mu x}$
- where μ is the linear attenuation coefficient.
  - Remember, this differs compared to charged particles.
  - Note similarity with equation of exponential decay of the activity of radionuclides.

Mass Attenuation Coefficient

- To eliminate density dependence of the attenuation coefficient, the linear attenuation coefficient is divided by density → mass attenuation coefficient, μ_m (SI units (m^2/kg)).
  - Dependent on the energy of incident photons and Z of medium.

Other Attenuation Coefficients

- Electronic attenuation coefficient

$$\mu_e = (\mu/\rho)*(1/N_o)\ m^2/\text{electron}$$

- Atomic attenuation coefficient

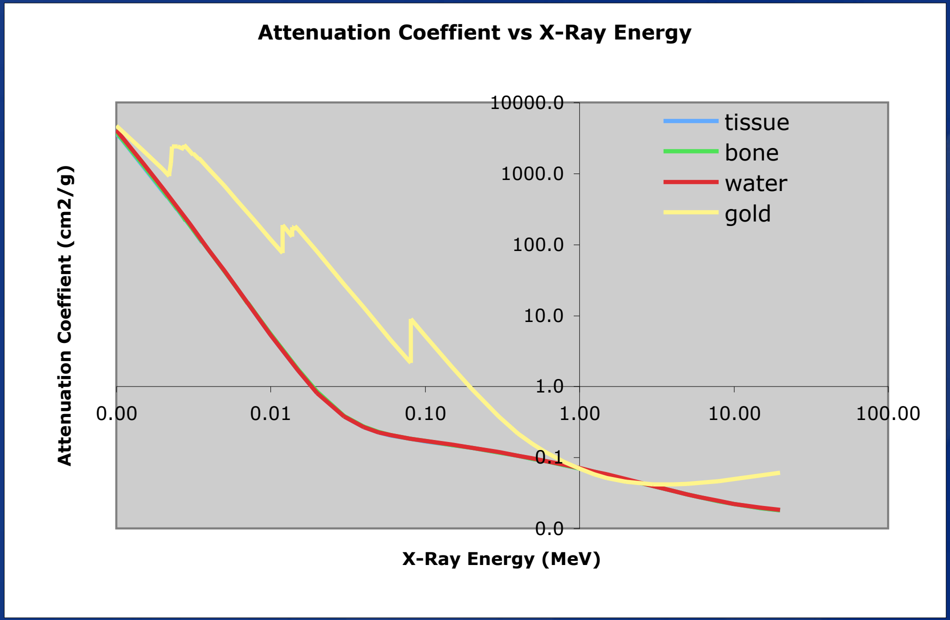
$$\mu_a = (\mu/\rho)*(Z/N_o)\ m^2/\text{atom}$$

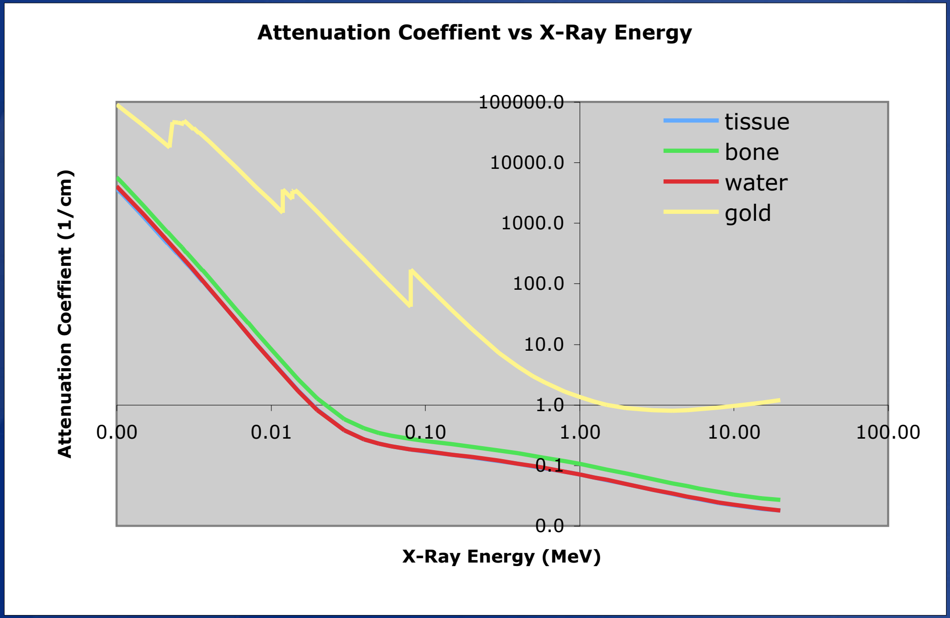
N_o = Avogadro's constant, $6.0221\text{x}10^{23}$ particle/mol.

Attenuation Coefficients (Cont.)

- The probability of an interaction is dependent on the number of atoms a photon encounters per unit distance. This will vary depending on the density of the material.
- Density is temperature dependent for gasses
  - $\mu_{solid} > \mu_{liquid} > \mu_{vapor}$
- For water, liquid is denser than ice (reason why ice cubes float):
  - $\mu_{water} > \mu_{ice} > \mu_{water\ vapor}$

Attenuation Coefficient vs. Photon Energy





Difference in attenuation small in therapeutic region – reason for poor quality port films.

Image Quality

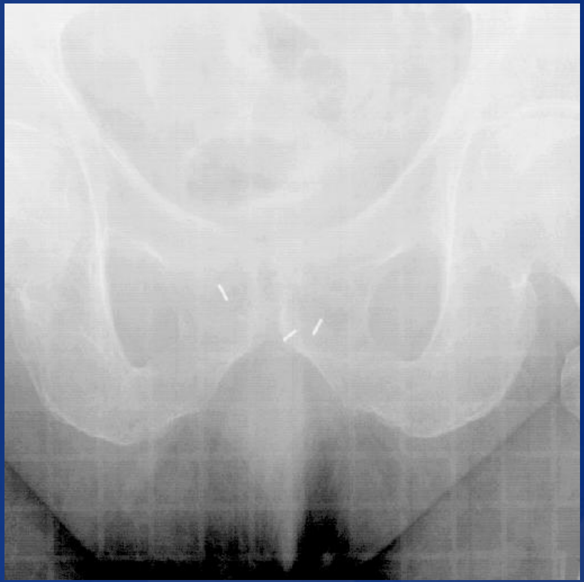


Image acquired at 75 kVp.

Predominate photon interaction – photoelectric.

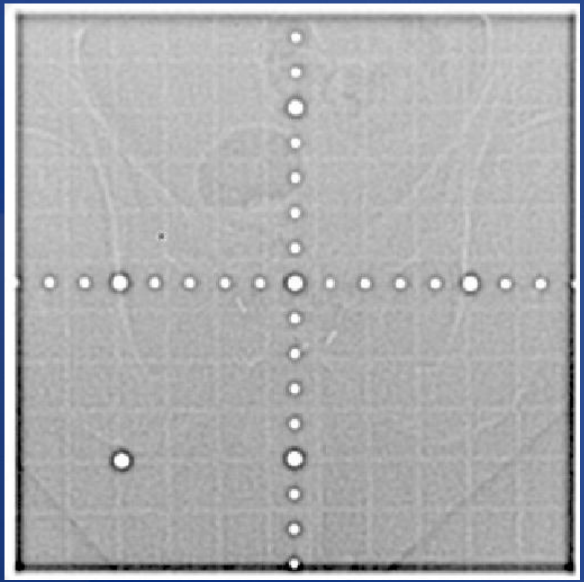


Image acquired at 6 MV.

Predominate photon interaction – Compton scatter.

Quality of image/contrast reflects differences in attenuation of x-ray beam. At energy range used in therapy, dominate interaction is Compton scatter. Image contrast degraded compared to image acquired at diagnostic energies.

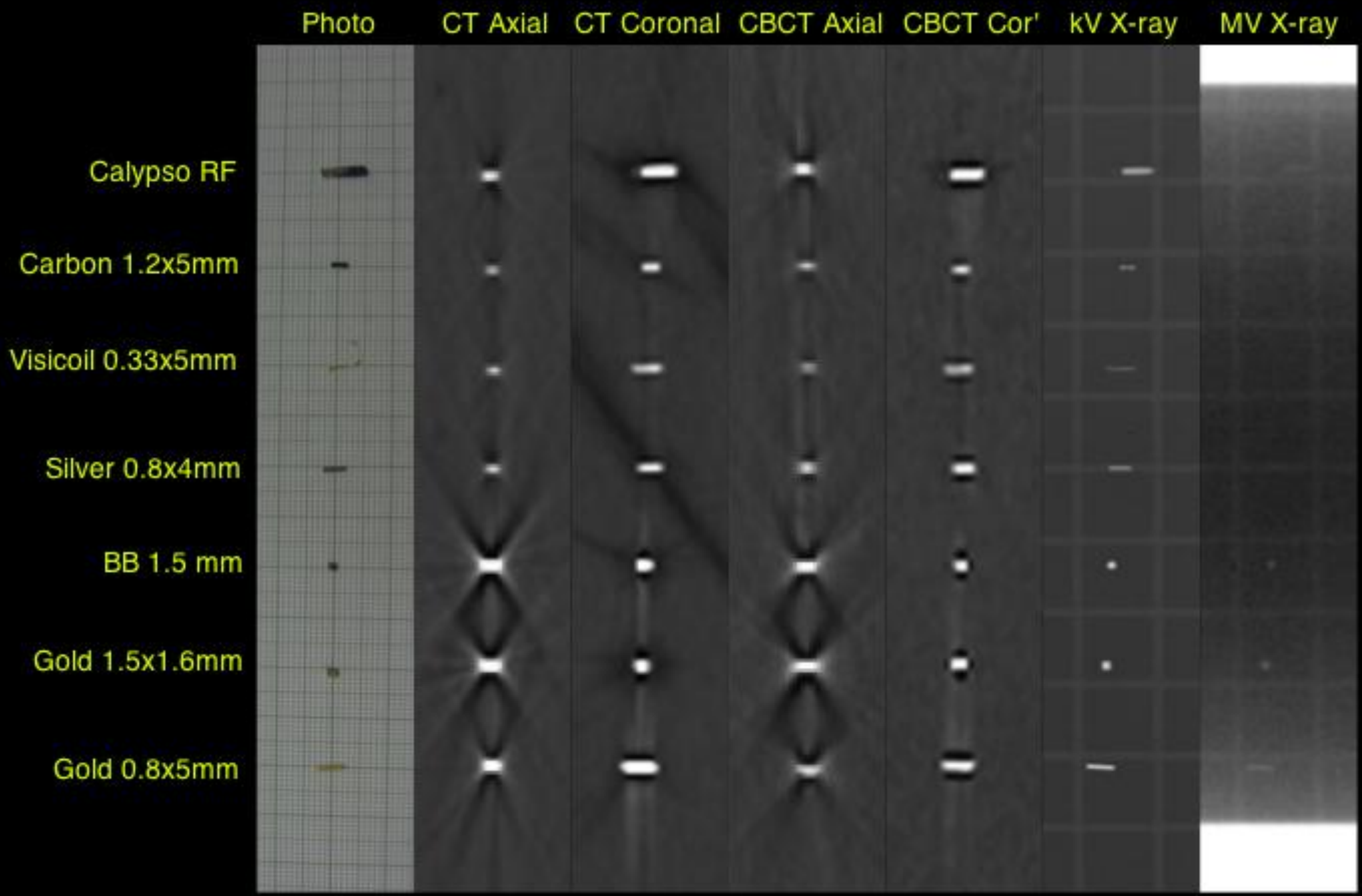


Photo
CT Axial
CT Coronal
CBCT Axial
CBCT Cor'
kV X-ray
MV X-ray
Calypso RF
Carbon 1.2x5mm
Visicoil 0.33x5mm
Silver 0.8x4mm
BB 1.5 mm
Gold 1.5x1.6mm
Gold 0.8x5mm

Interactions of Particulate Radiation with Matter

- Charge Particles
- Explanation of CSDA
- How ionization becomes dose
- High and Low LET and RBE

What are Charged Particles?

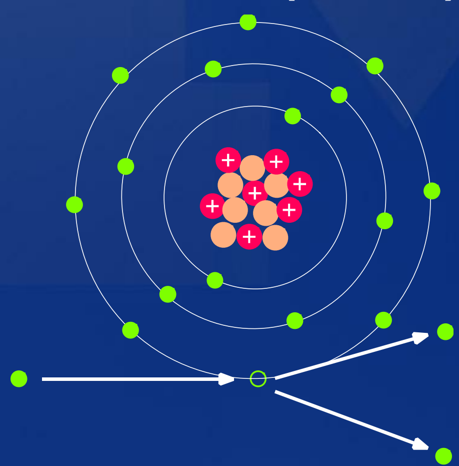
- e.g. electrons, positrons, protons …
- Have a charge + or -
- Magnetic dipole
- Have mass

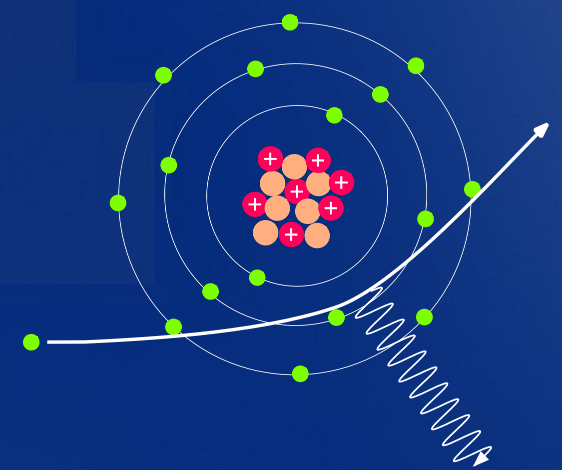
Two things can happen!

- Ionize
  - Atomic Interaction
  - Energy -> Electron
  - Radiative Loss

  OR

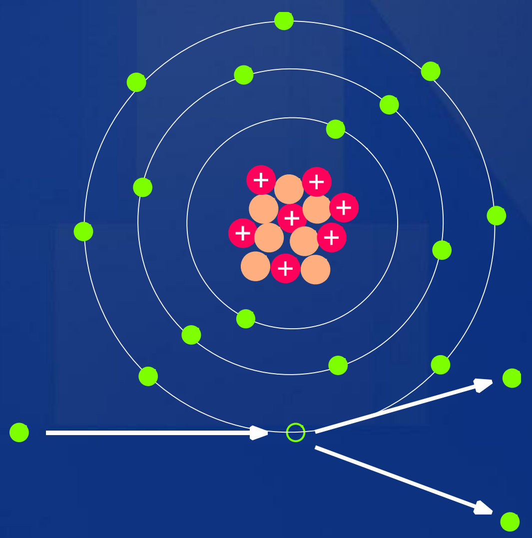
  - Ionization (Dose)
- X-rays
  - Nuclear Interaction
  - Bremsstrahlung
  - Spectrum of X-ray

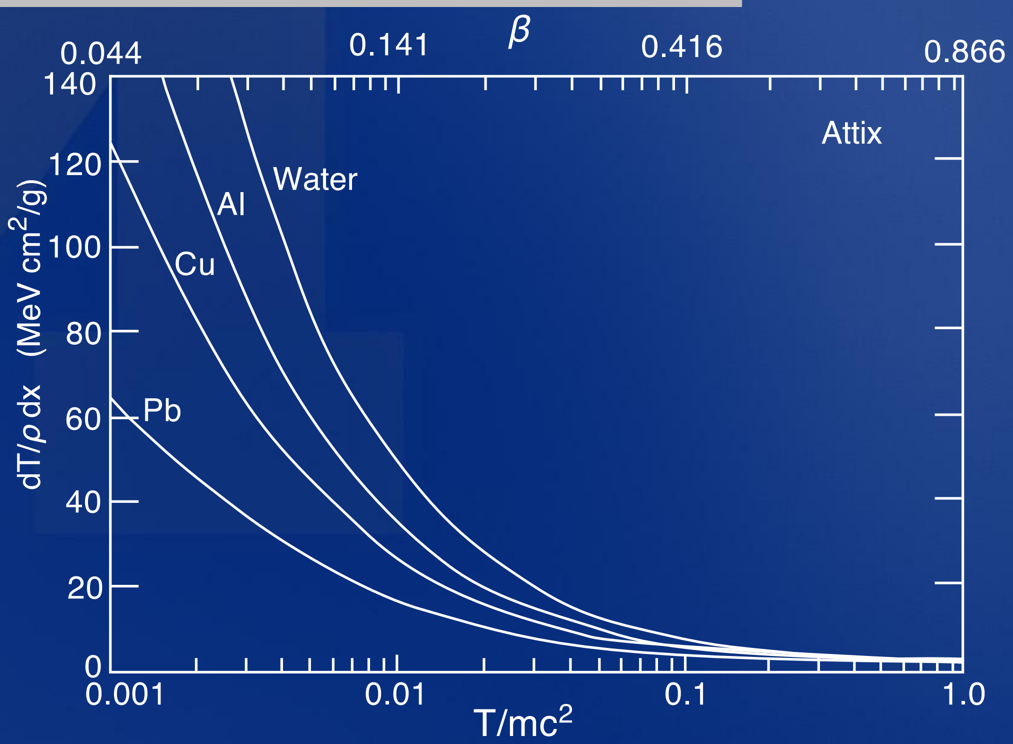




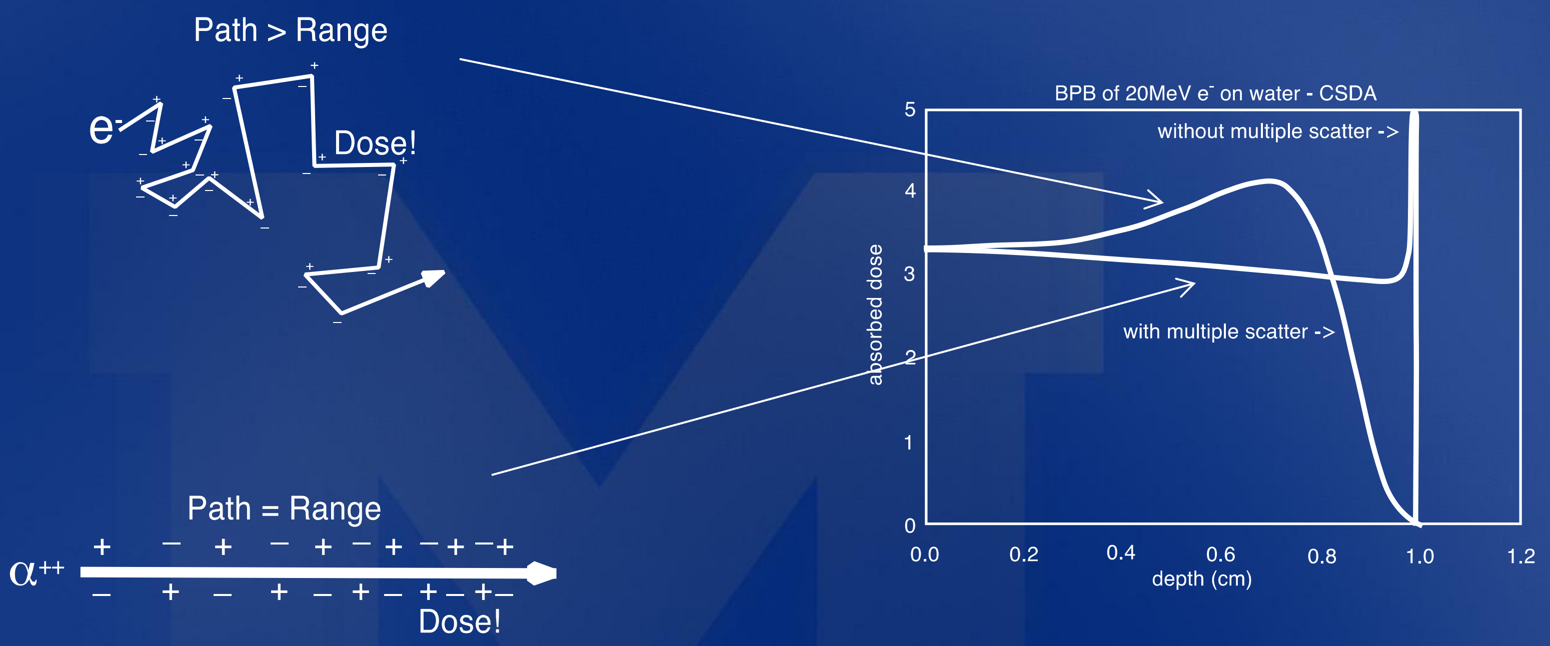
Energy Loss of Charge Particles Continuous Slowing Down Aprox

$$-\frac{dE}{dx}=\frac{4\pi z^2 e^4}{mv^2}n_e\left[\ln\left(\frac{2\gamma c^2 m}{I'}\right)+\frac{1}{2}\right]$$





Path Length of Charged Particles



Because of their small mass, electrons undergo multiple scattering in tissue. As a result, a Bragg peak not observed for electrons, it is smeared out.

Direct vs. Indirect Ionization

- Direct ionization –
  - Interaction of charged particles with matter.
  - Charged particles deliver their energy directly to matter through a series of many coulomb interaction along the particle's path.
- Indirect ionization –
  - Interaction of uncharged particles (x-rays, gamma rays or neutrons) with matter.
  - Uncharged particles first transfer their energy to charged particles in matter in a relatively few large interactions.

X-ray Production
Bremsstrahlung

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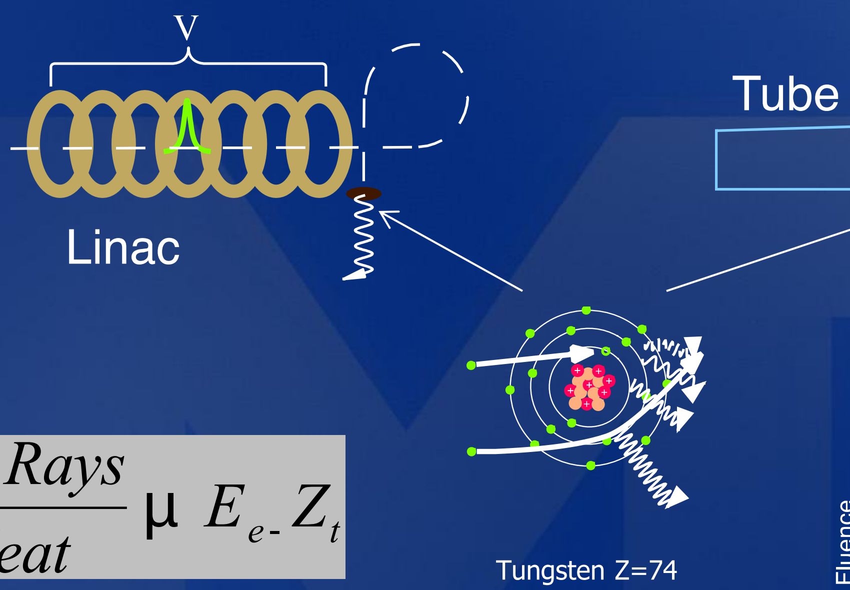
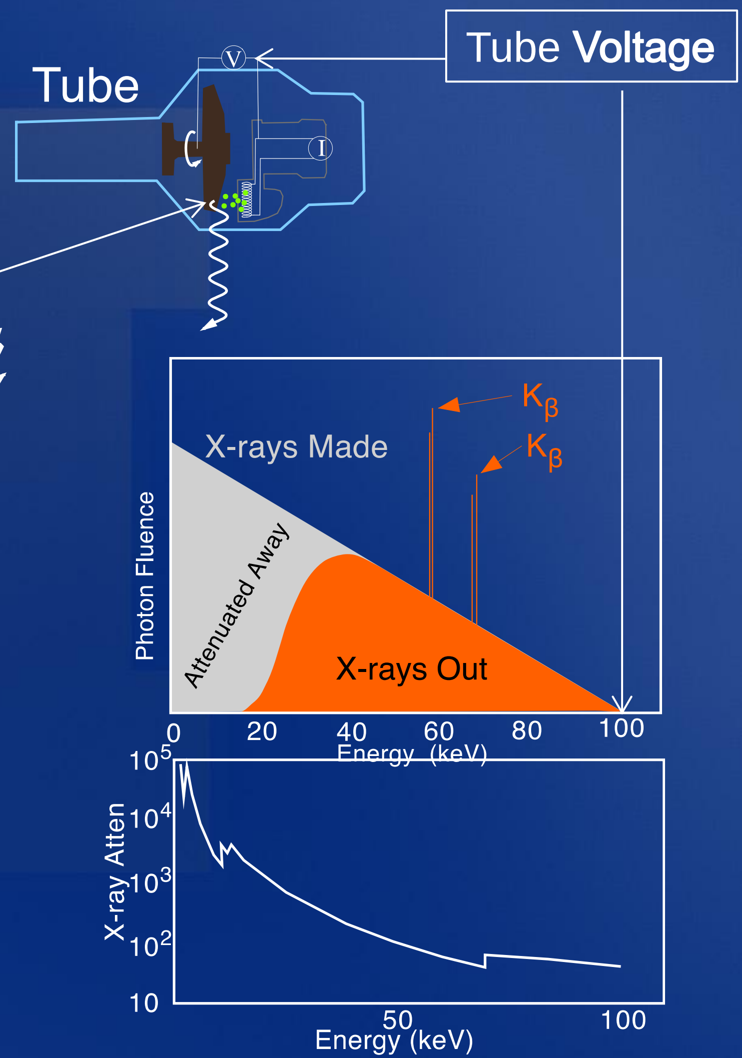
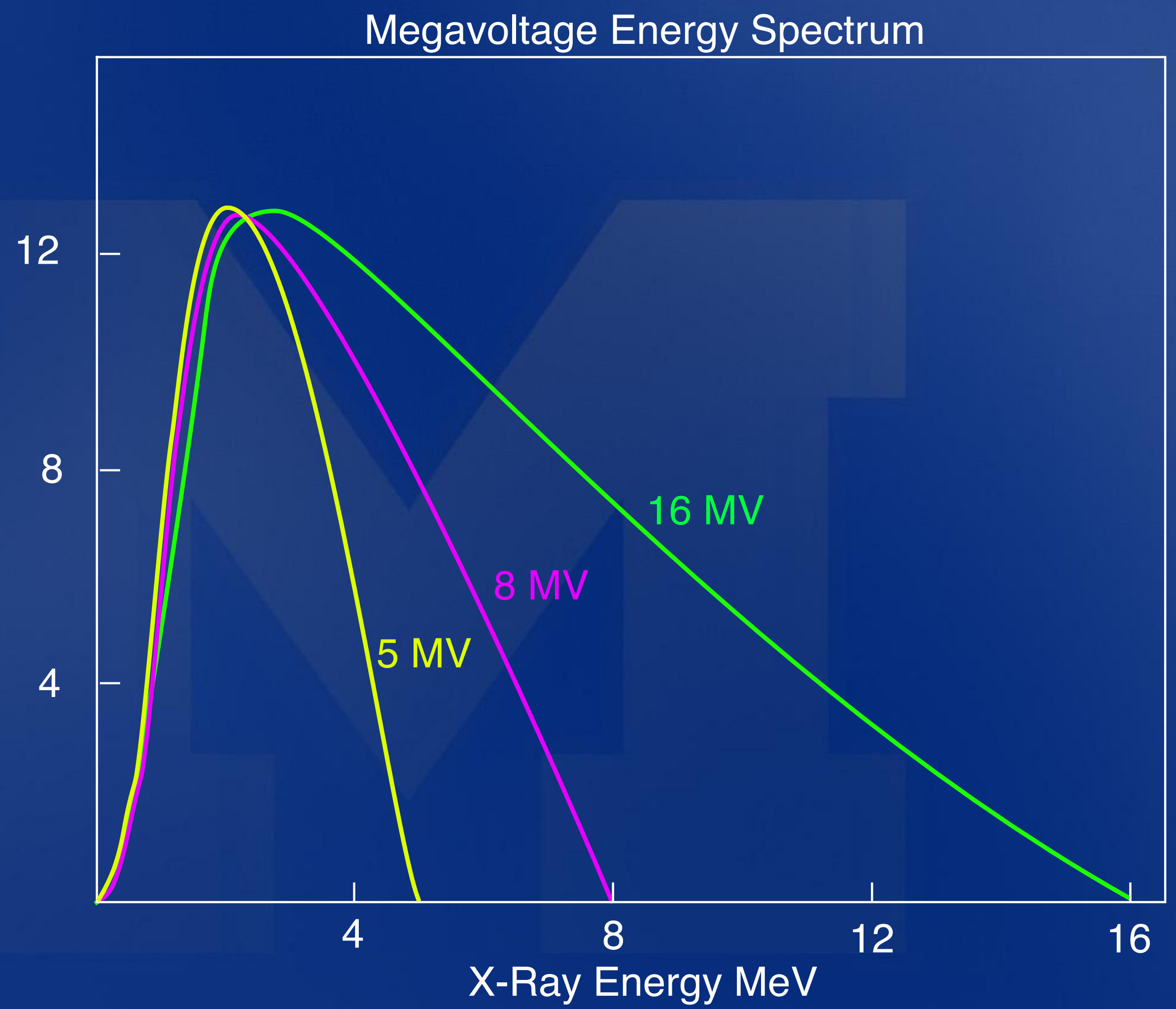




$$\frac{X\text{ - }Rays}{Heat}\ \mu\ E_{e-}Z_t$$

Operating Voltage (kV)	% Energy Into Heat	% Energy Into X-Rays
60	99.5	0.5
100	99.5	0.5
200	99.0	1.0
4000	60.0	40.0
20000	30.0	70.0

Polychromatic Spectrum



Sauer and Neumann. Reconstruction of high-energy bremsstrahlung spectra by numerical analysis of depth-dose data. Radiotherapy and oncology : journal of the European Society for Therapeutic Radiology and Oncology (1990) vol. 18 (1) pp. 39-47

Photon Impinging on Medium

- Photons traveling through a medium can be transmitted, absorbed, or scattered.
- Primary radiation - photons that traverse a medium without having interacted.
- Secondary radiation - photons that have been scattered by medium that result in a change in direction and/or lose of energy of incident photon.

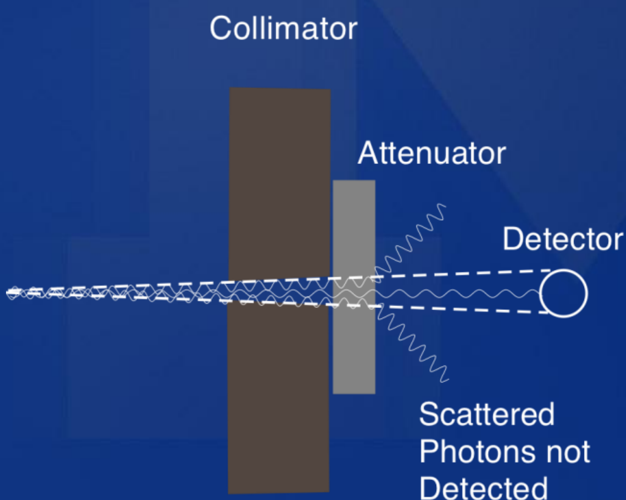
Attenuation of Photons

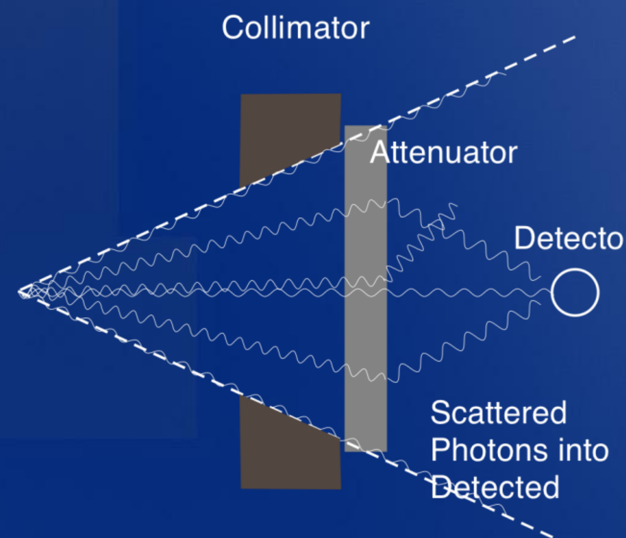
- The removal of photons as a result of tissue absorption and scatter from a photon beam as it passes through matter.
- Measure of attenuation is dependent on the detection geometry.

Narrow vs. Broad Beam Geometry

- Narrow beam ("good" geometry)
  - Radiation to detector *only* from primary radiation, excludes scatter.

- Broad beam ("poor" geometry)
  - Detector receives primary radiation and substantial amount of scatter.
  - Scattered photon lower in energy and underestimates attenuation of beam.





Characteristics of Photon Beams

- Energy
  - Accelerating potential
  - Beam Quality
  - Flatness and Symmetry
  - Penumbra

HVL

- Reduction in beam intensity can be expressed as $(1/2)^n$, where n is number of HVL's.
  - For example, number of transmitted photons through 5 HVL's is:

$$(1/2) \times (1/2) \times (1/2) \times (1/2) \times (1/2) = (1/2)^5 = 0.031 \text{ or } 3.1\%$$

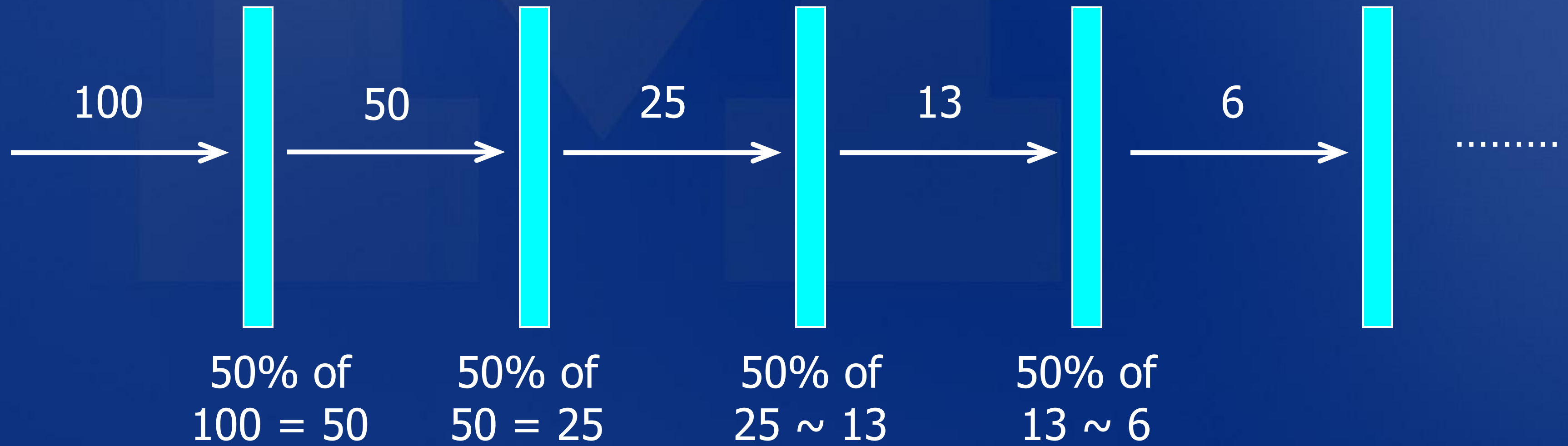
Half-Value Layer (Monoenergetic beam)

- HVL – thickness of material required to reduce the intensity or number of photons transmitted through a medium by ½.

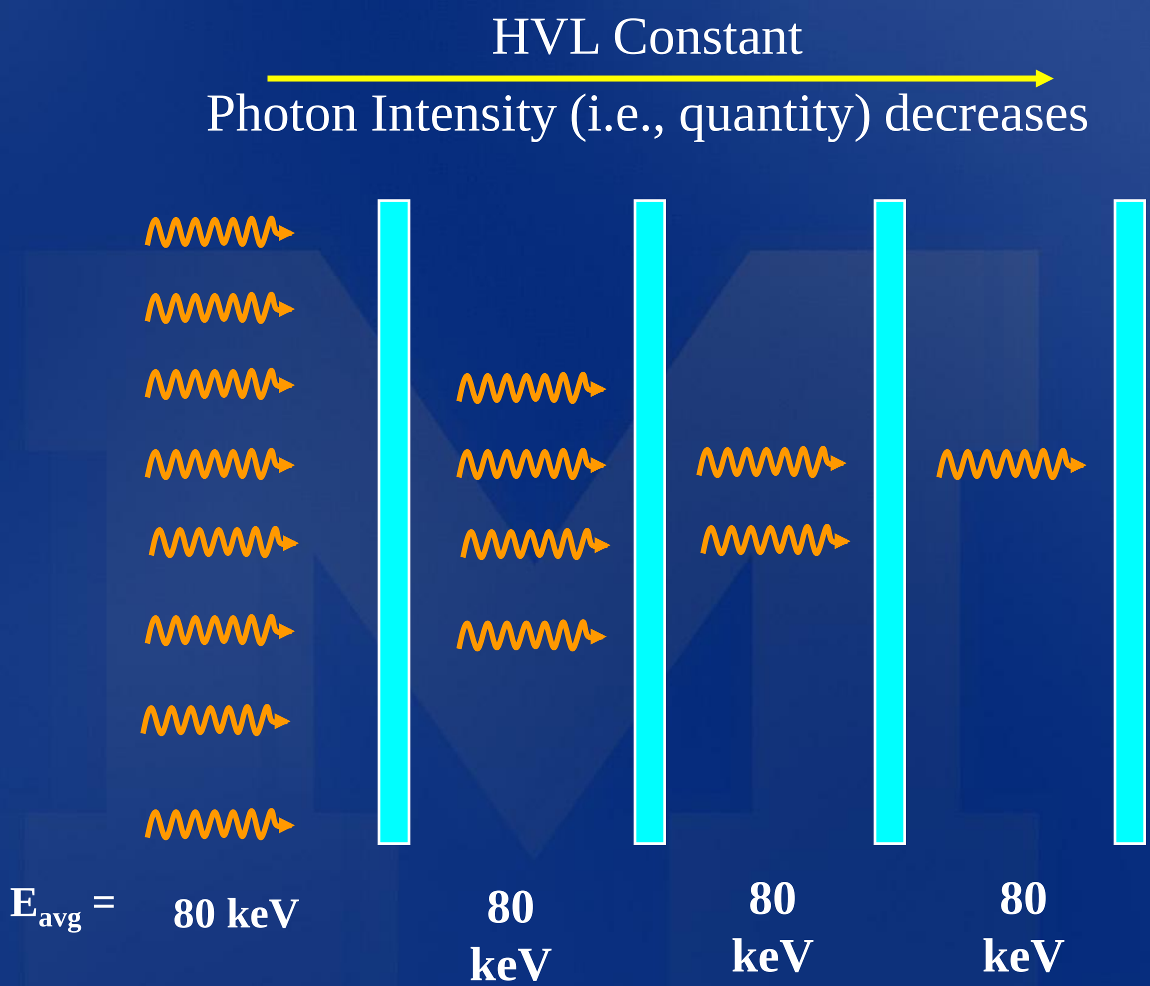
$$N/N_o = ½ = \exp(-\mu x)$$

$$\ln(1/2) = -0.693 = -\mu x$$

$$x = HVL = 0.693/\mu$$



Monoenergetic Radiation



As a monochromatic beam traverses matter, number of photons reduced, but average beam energy constant. Thus, HVL is constant, $HVL_1 = HVL_2 = \ldots = HVL_n$.

Tenth-Value Layer

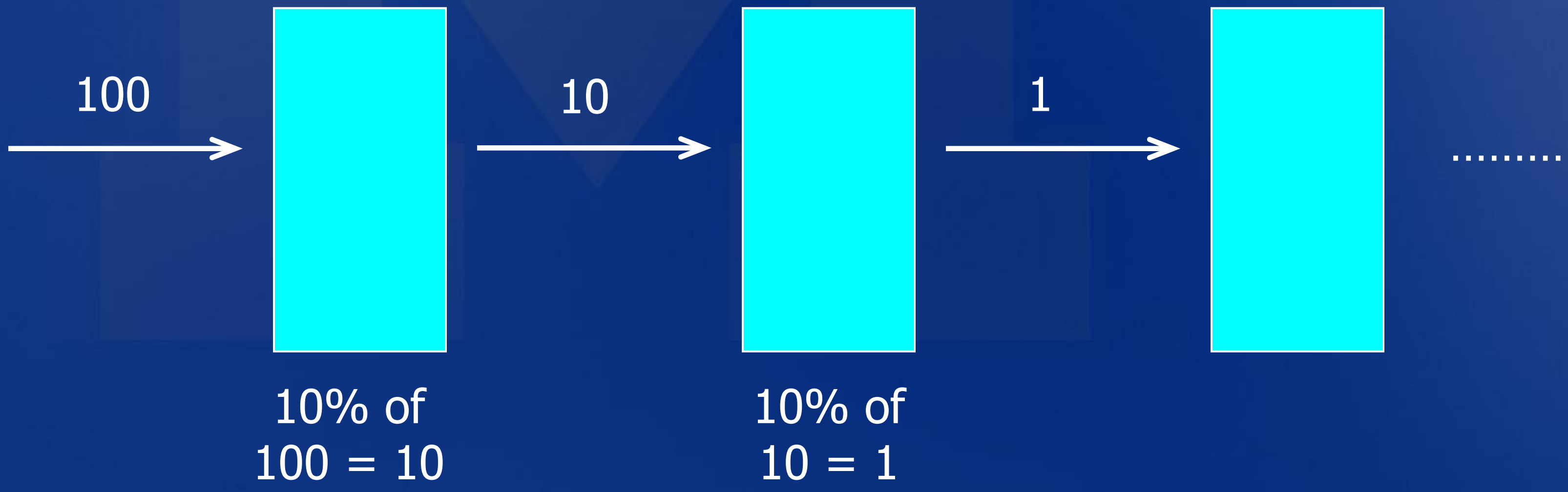
- TVL – thickness of material that attenuates photon beam by 90%, only transmits 1/10th of incident beam.

$$N/N_o = 1/10 = \exp(-\mu x)$$

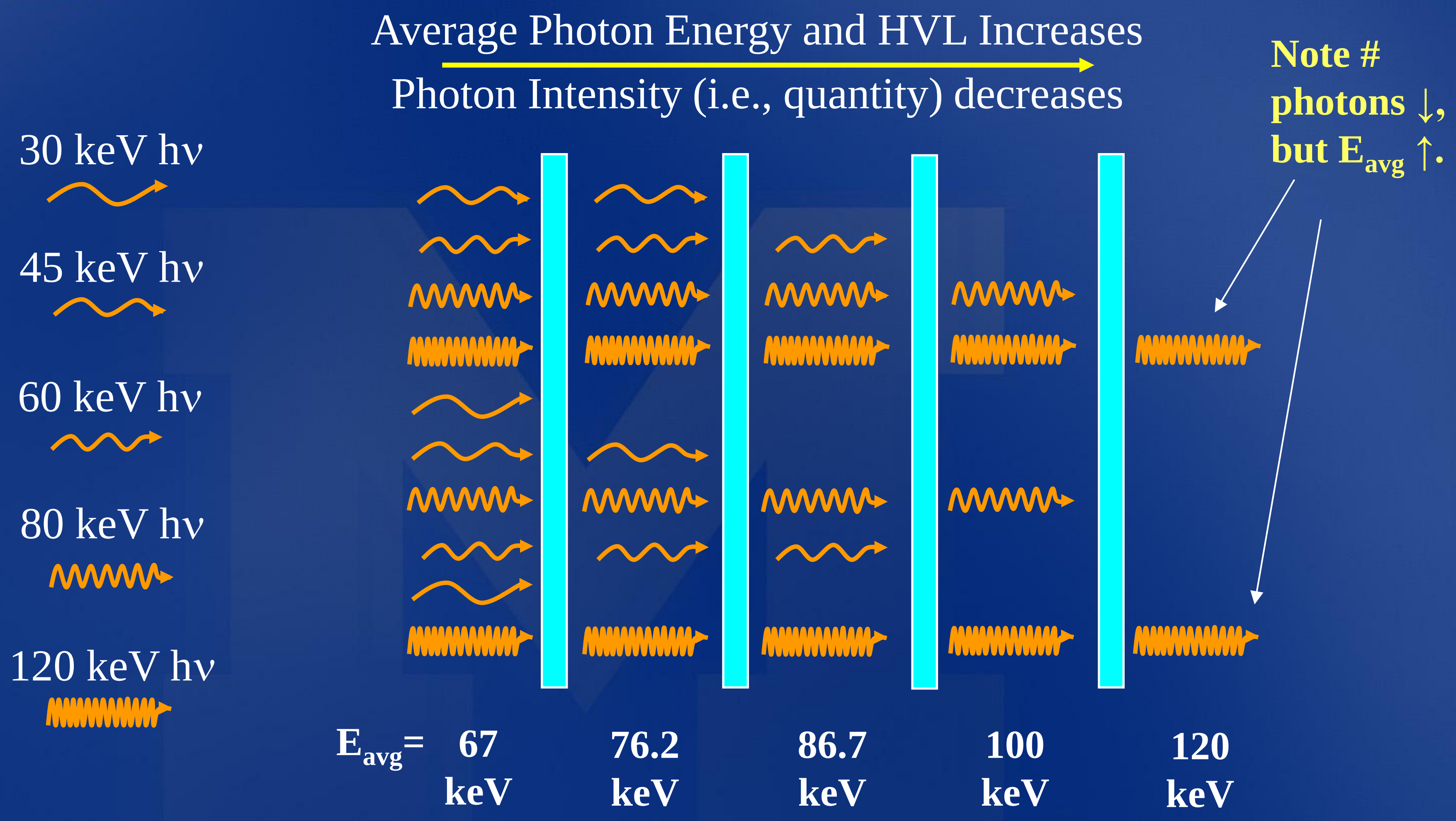
$$\ln(1/10) = -2.303 = -\mu x$$

$$x = TVL = 2.303/\mu$$

  - Often used for shielding calculations.



Polychromatic Radiation



As a polychromatic beam traverses matter, beam hardens which results from preferential loss as low energy photons are filtered from beam.

Transmission of Polychromatic Radiation

- Transmission of polychromatic radiation CANNOT be described simply by

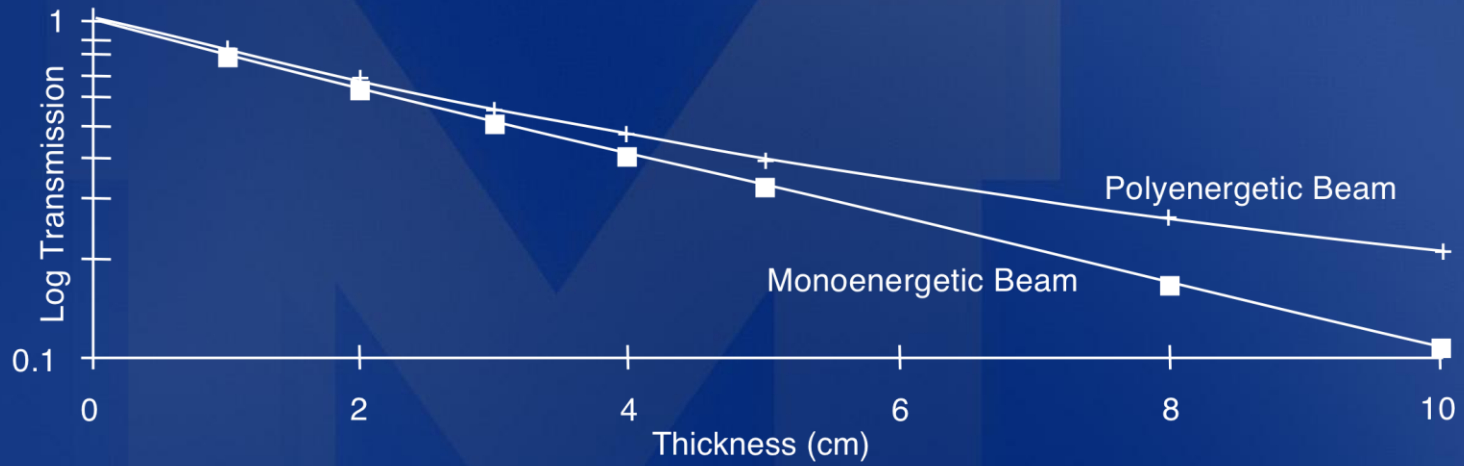
$$I = I_0 e^{-\mu x}$$

- Each photon energy is attenuated differently, thus μ varies.

HVL – Polychromatic Radiation

- As beam hardens, it will take more material to attenuate the beam. Thus, HVL increases.
  - $HVL_n > \ldots > HVL_2 > HVL_1$

Monochromatic Approximation



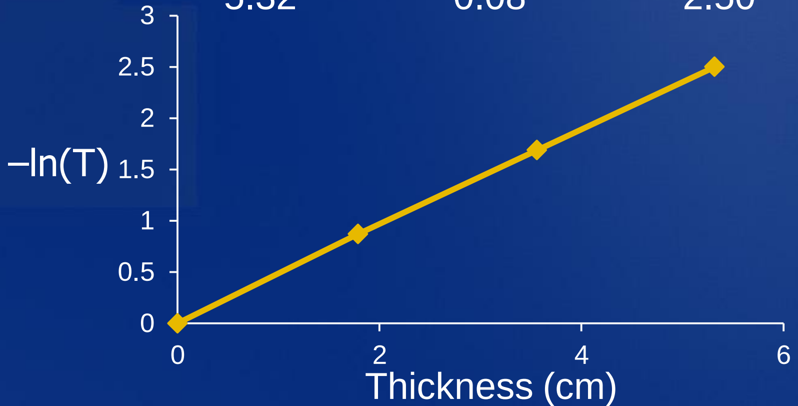
- Approximation - over first few centimeters of material, μ slowly varies.

$$\mu_{eff} = 0.693/HVL_{poly}$$

Practical Application TBI Blocks

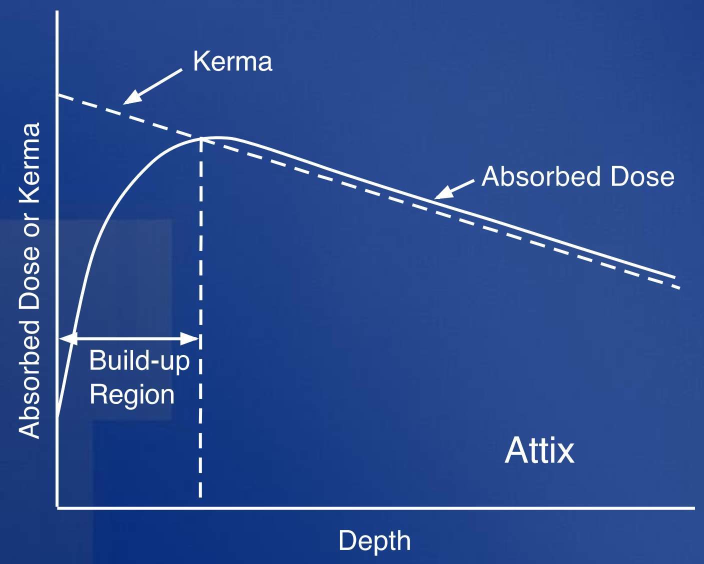
- Transmission lung block
  - Custom block to reduce dose to lung
  - Made from Cerrobend (50% Bi, 27%Pb, 13%Sn, 10% Cd)
  - Specific transmission
- Fabricate Test Blocks
  - Measure transmission T= I/I_o
  - Plot –ln(T) vs thickness
  - Transmission table

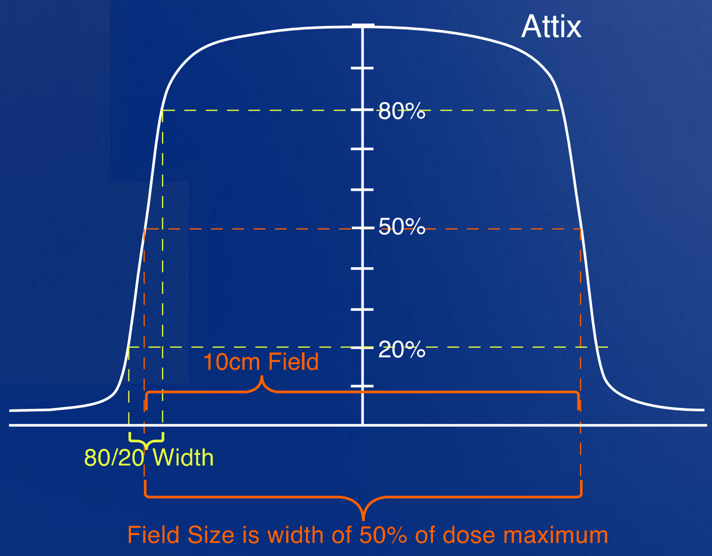
Thickness (cm)	T	-ln(T)
0	1	0
1.79	0.42	0.87
3.56	0.18	1.69
5.32	0.08	2.50



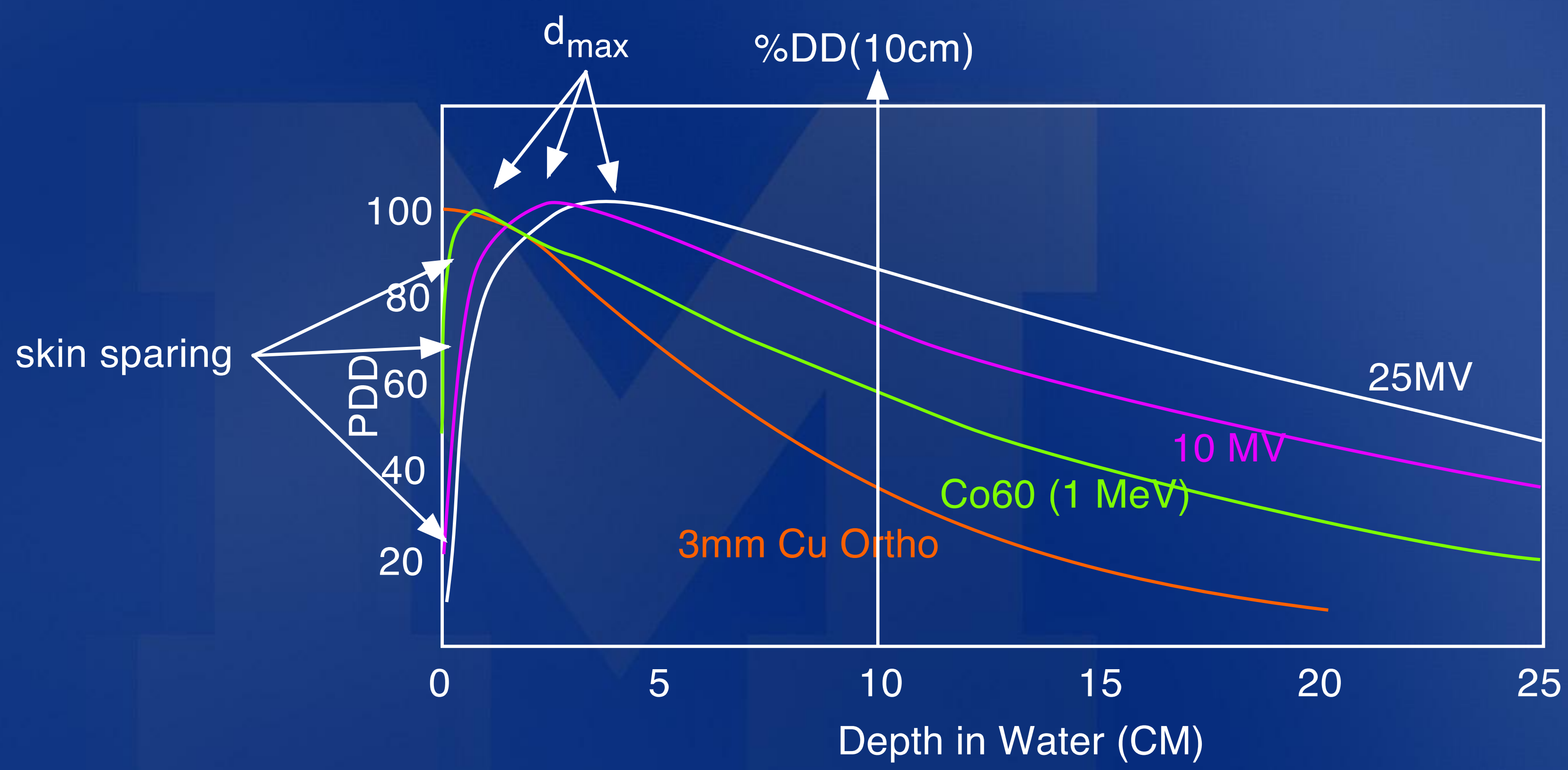
Beam Characteristics

- Surface Dose
  - Contaminating e^-
  - Backscatter
- Build-Up Region
  - Lack of up stream e^-
- Penumbra
  - 50% defines field size
  - 80/20 width of penumbra



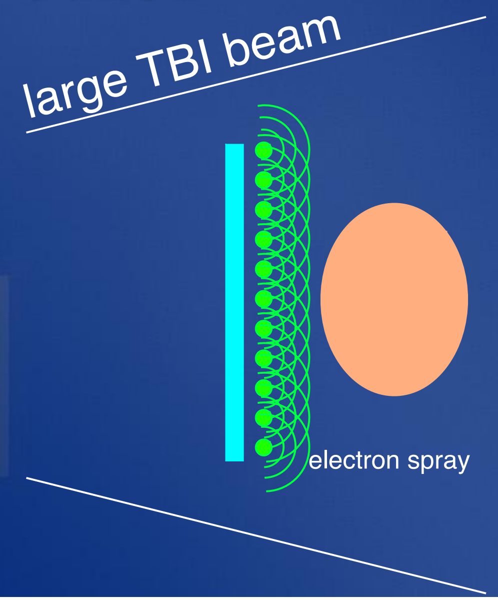


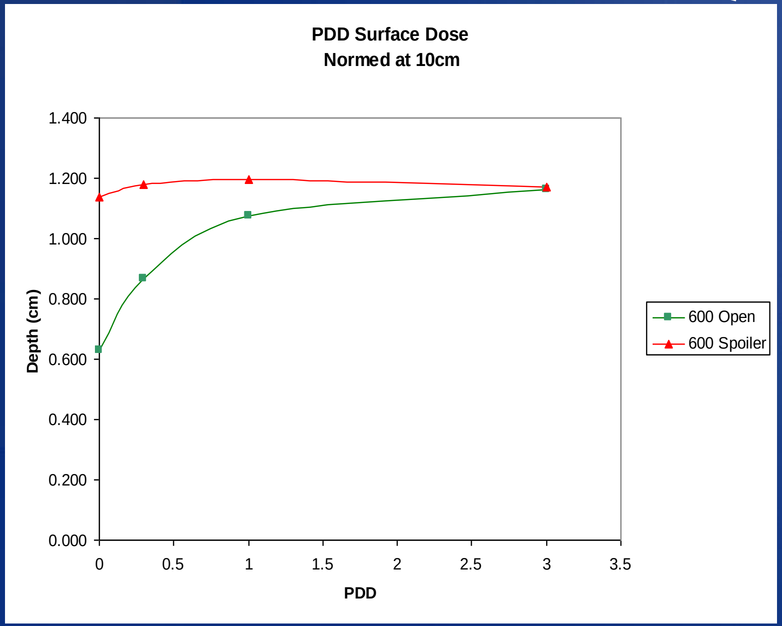
Beam Characteristics



Example TBI Beam Spoiler

- 4x8 Feet Plastic Sheet
- Increase the skin dose
- Pre-Build Up
  - Electron spray





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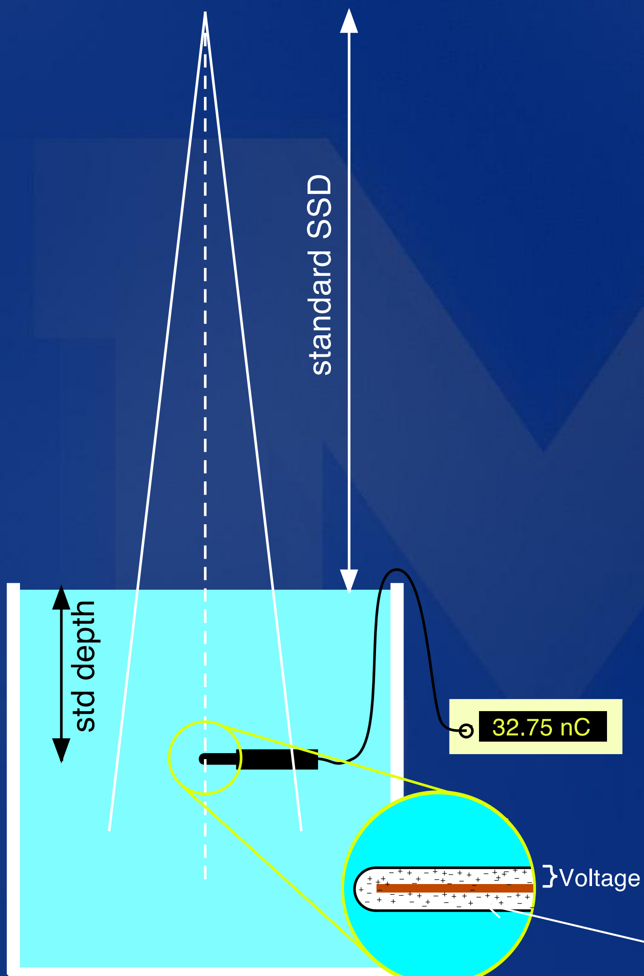
Quantification and Measurement of Dose



$$D_w = X\frac{\overline{W}}{e^-}\left(\frac{\mu_{en}}{\rho}\right)_{air}^{w}$$

$$D_{air} = X\frac{\overline{W}}{e^-}$$

X-ray beam

e^- interaction

$$X = \frac{dQ}{dm} = \Psi\left(\frac{\mu_{en}}{\rho}\right)\left(\frac{e}{\overline{W}}\right) = K_c\left(\frac{e}{\overline{W}}\right)$$

X-ray Interaction

Exposure X = Charge/mass

SI Exposure, Dose and Dose EQ Units (ICRU Report 85)

- Exposure X measured in Roentgen (R)
  - 1R=2.58 x 10^{-4} C/kg
- KERMA (Kinetic Energy Release per unit MAss)
  - Units of J/kg
- Dose D measured in Gray (Gy)
  - 1 Gy = J/kg
  - 100cGy = 1Gy
  - 1 rad = 1 cGy
- Dose Equivalent H measured in …
  - H=DQ where
    - Q = (1 for X and e^-, 5 for slow n & p, 20 for fast n and alpha)
  - rem roentgen equivalent man
  - SI unit is the Sievert Sv (J/kg)