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Physics of Particle Beams

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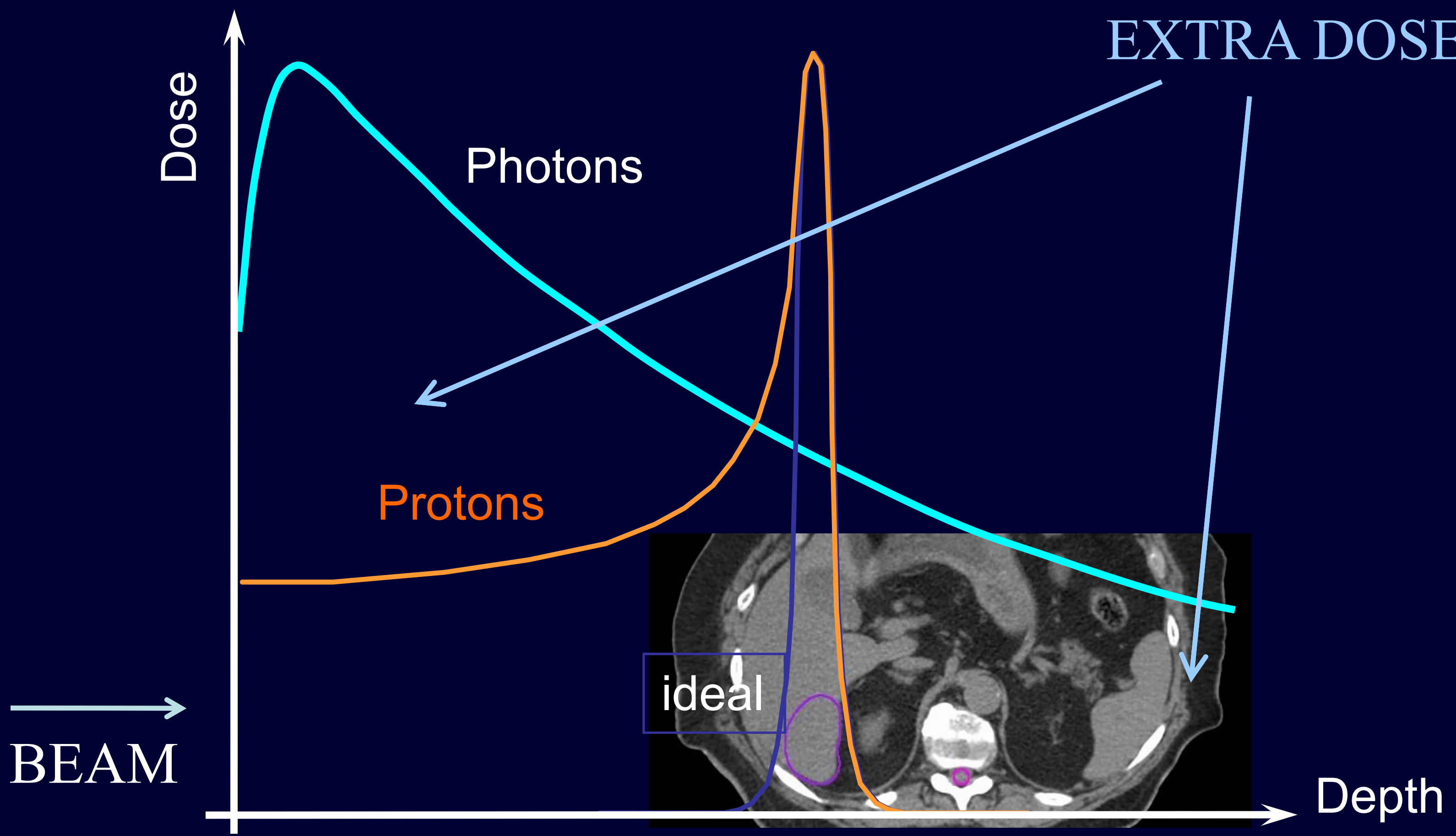
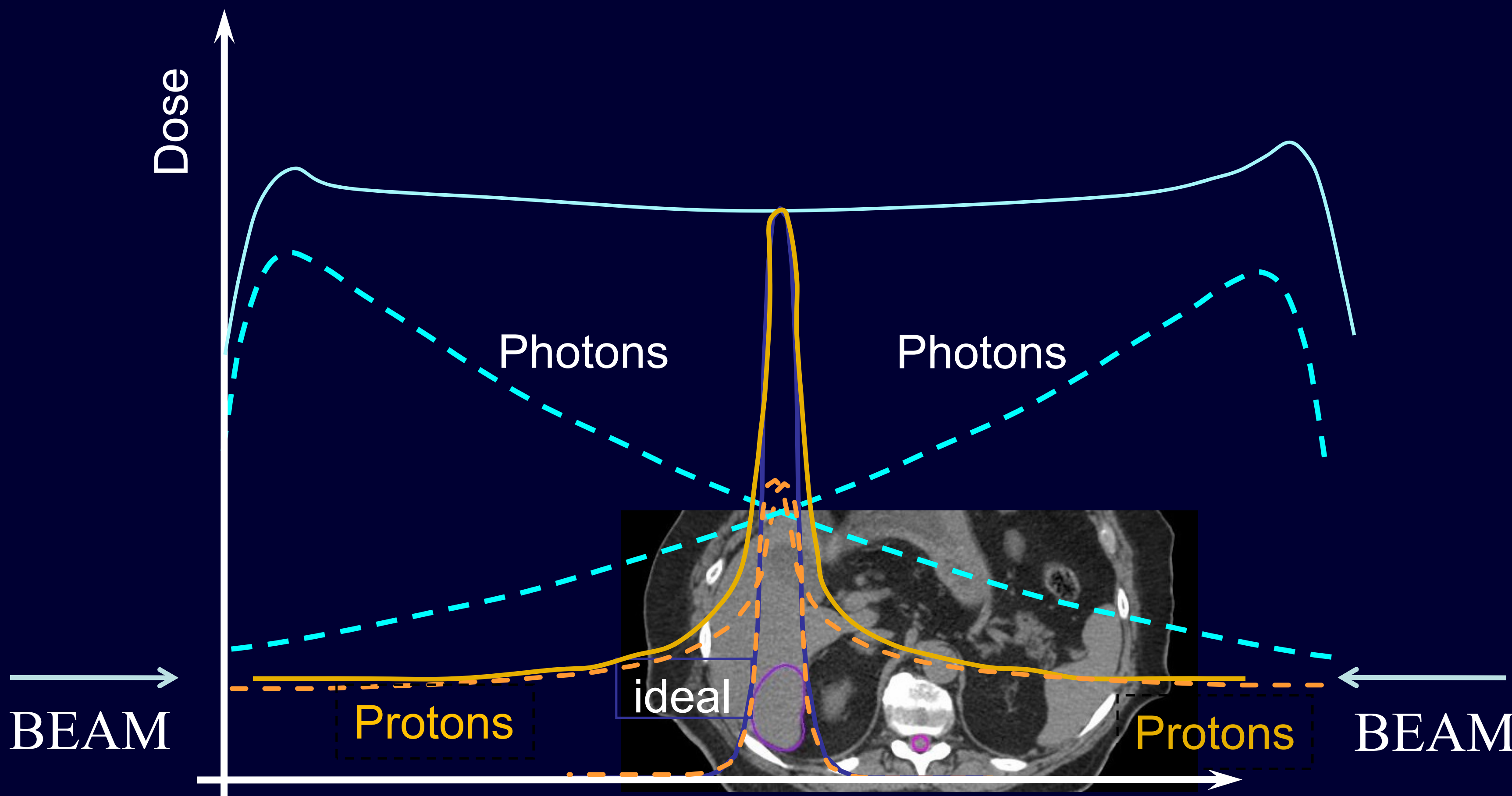
External Beam Therapy



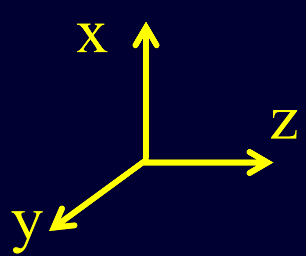
Photon vs Proton

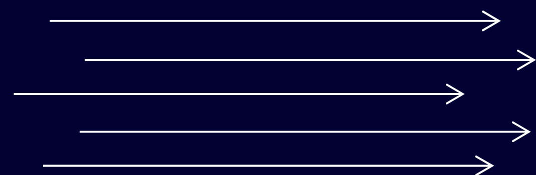
Proton Beam Advantage



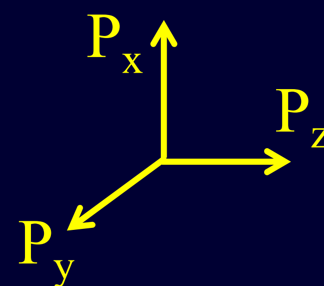
Beam for beam you can always do a better job with particles (except at the surface). *Flanz '09*

A Beam is a Bunch of Particles

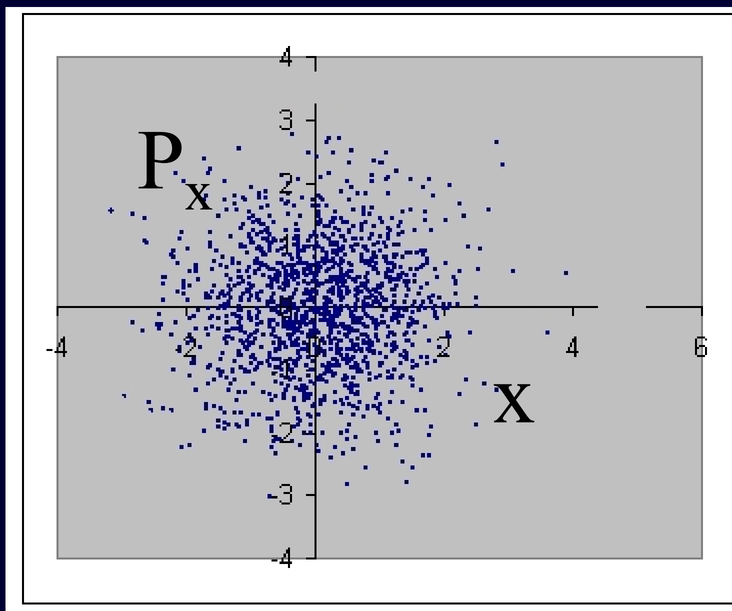




(protons, carbon ions, photons, electrons, …)



Phase space diagram



A beam is a collection of many particles all of whose <u>longitudinal</u> and <u>transverse</u> momentum are close enough and remain more or less close to each other.

Particles of Interest

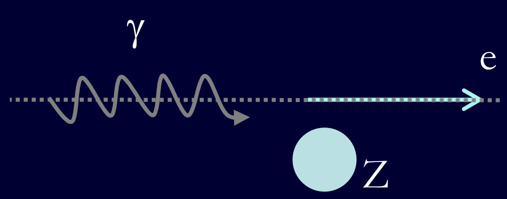
- Photons (γ, X ray)
  - Charge: 0
  - Indirect Ionization
- Electrons
  - Charge: -1
  - Direct Ionization
  - Mass: 0.512 MeV

- Protons
  - Charge: +1
  - Direct Ionization
  - Mass ~ 938 Mev (2,000 • m_e)
- Carbon ions
  - Charge: +6
  - Direct Ionization
  - Mass ~ 12 • m_p

Photon Interactions with Matter

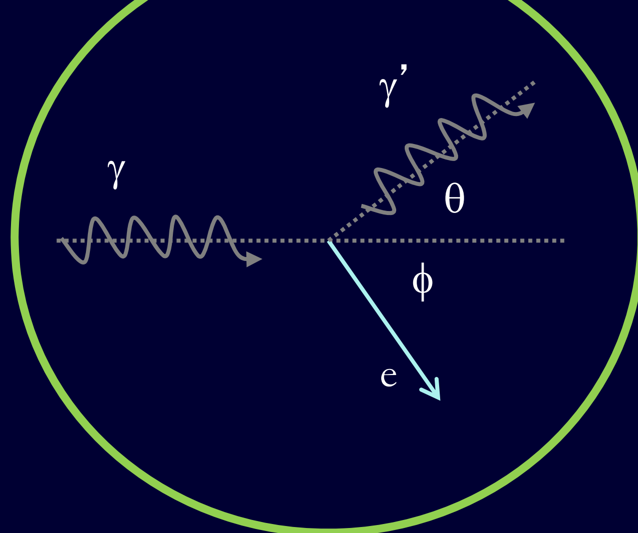
Photoelectric Effect

Photon ejects electron from an atom.



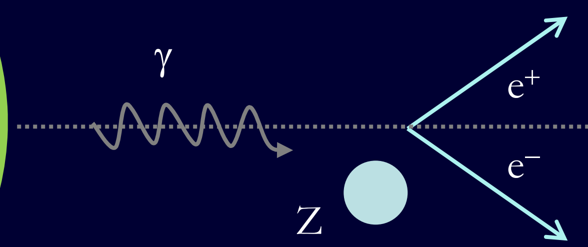
Compton Effect

Photons scattering from atomic electrons.



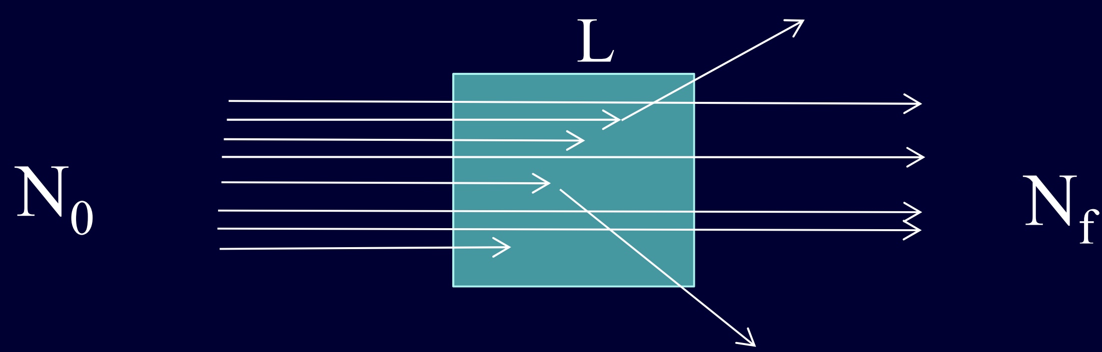
Pair Production

Photons above twice the electron rest mass energy can create a electron positron pair.



Photons absorbed or scattered, out of the beam

Photons --- Attenuation

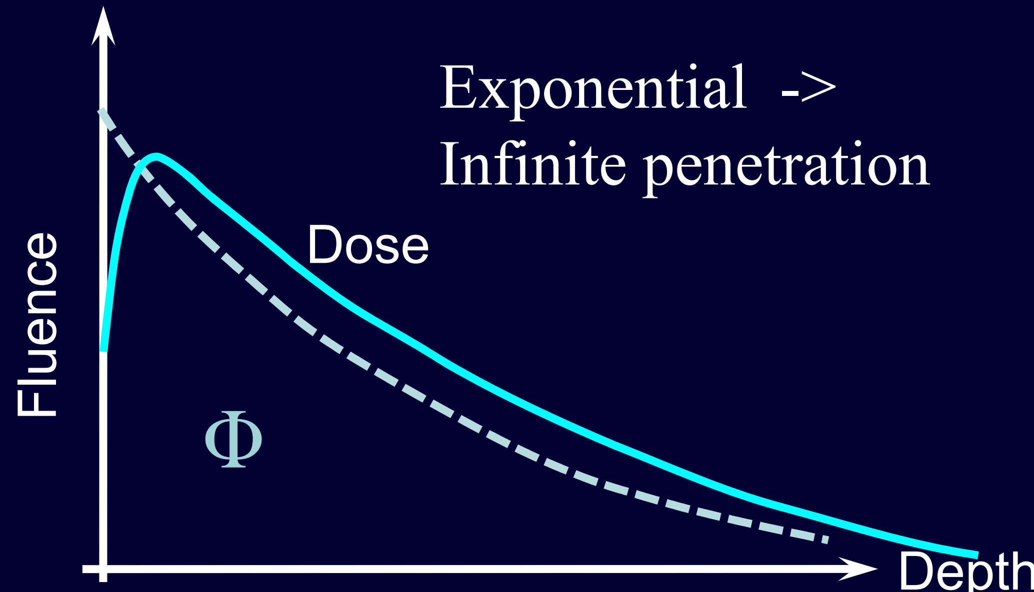


Number of photons decreases exponentially

$$N_f = N_0\, e^{-\mu L}$$

Fluence:

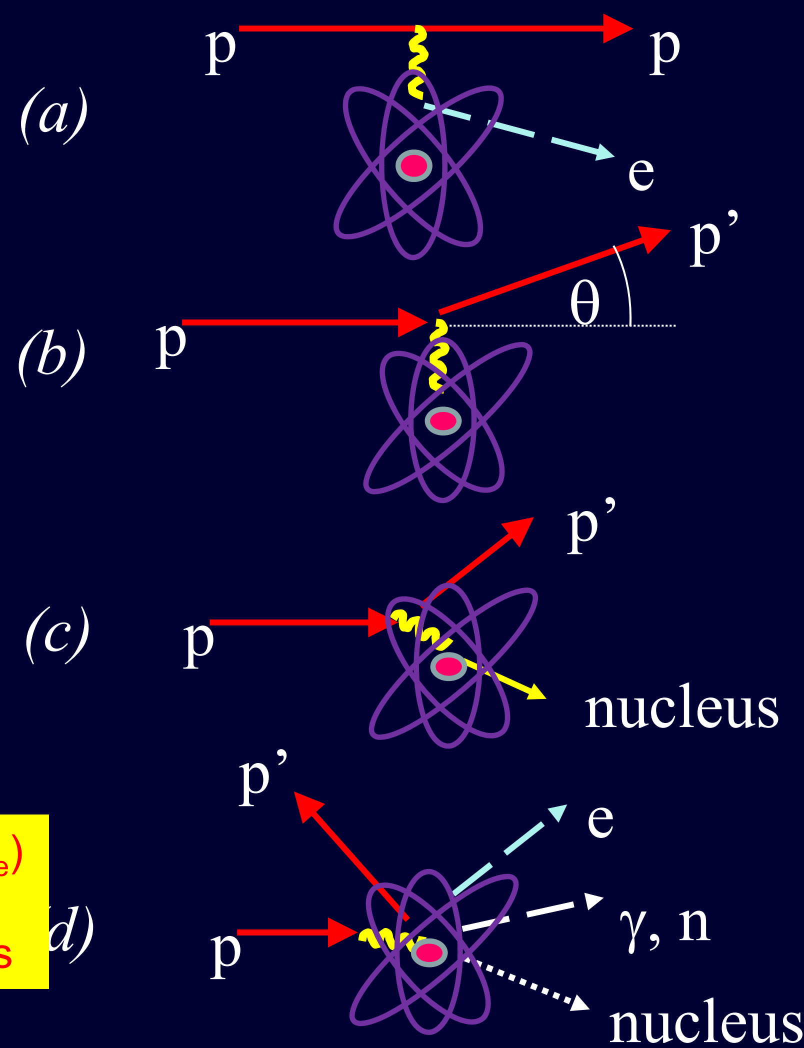
$$\Phi = N / A$$



Exponential -> Infinite penetration

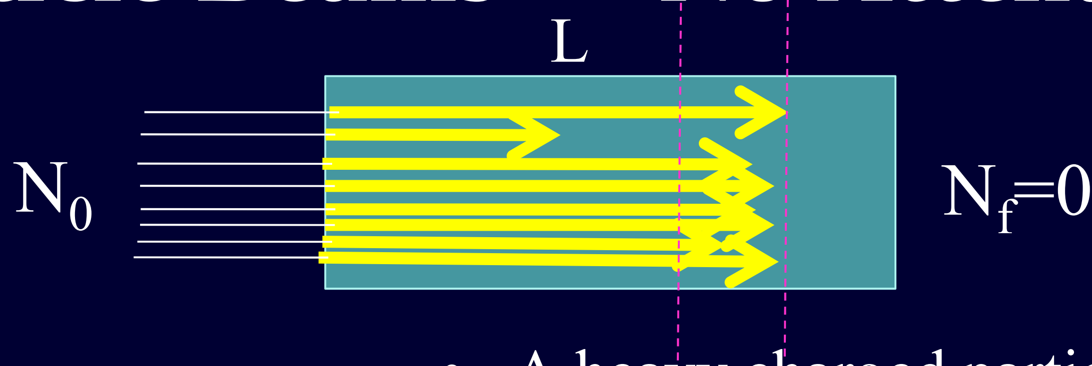
Proton Interactions with Matter

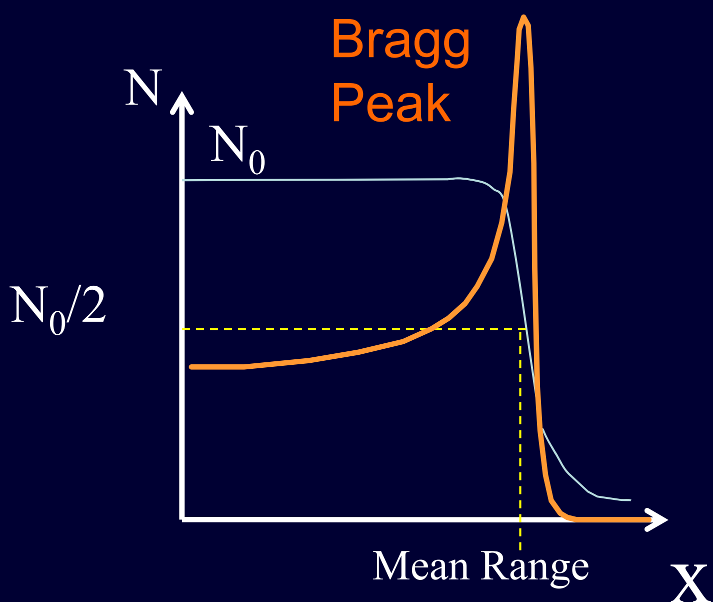
- With *electrons* mediated by Coulomb force (*a*)
  - *Excitation*
  - *Ionization*
- With *nucleus* mediated by Coulomb & nuclear forces (*b-d*)
  - *Multiple Coulomb scattering (b), small θ*
  - *Elastic nuclear collision (c), large θ*
  - *Inelastic nuclear interaction (d)*



Mean electron energy E_{mean} very low (m_p>> m_e)
E_{mean} independent of proton kinetic energy
Interaction probability higher for slower protons

Particle Beams --- No Attenuation





- A heavy charged particle endures multiple interactions through matter, but “stays” in the beam, because it is deflected only slightly.
- It loses only a small fraction of its energy in each interaction (except in “rare” nuclear interactions) until it stops, i.e., continuous slowing down.
- It deposits most energy near the end

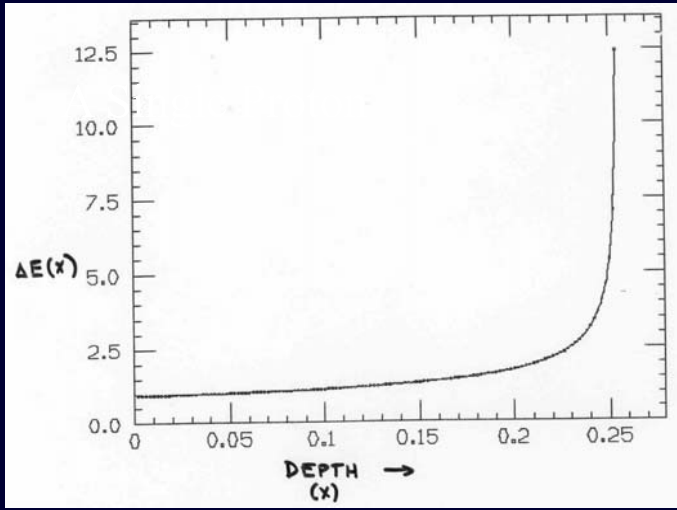
Ionization Energy Loss

- Energy of a charged particle dissipated by ionizing collisions:
  - E = Nw, where:
    - N = total number of **ion pairs** created
    - n = specific Ionization (ion pairs/unit length)
    - w = Energy required to produce an ion pair
    - w ~30-35 eV for organic matters
  - dE/dx = -S = -wn, where
    - S = Stopping Power (Linear Energy Transfer, LET)
- Mass stopping power:

$$\frac{S}{\rho} \equiv -\frac{1}{\rho}\frac{dE}{dx} \qquad \frac{\text{Mev}}{\text{g/cm}^2}$$

$$D = \Phi \; \frac{S}{\rho}$$

Dependence on Particle Charge and Velocity



- The **stopping power** FOR A GIVEN MEDIUM depends on the particle velocity and charge,
  - *Proportional to z^2*
  - *Inversely proportional to v^2*
  - Not dependent upon the Mass

Ionization Stopping Power

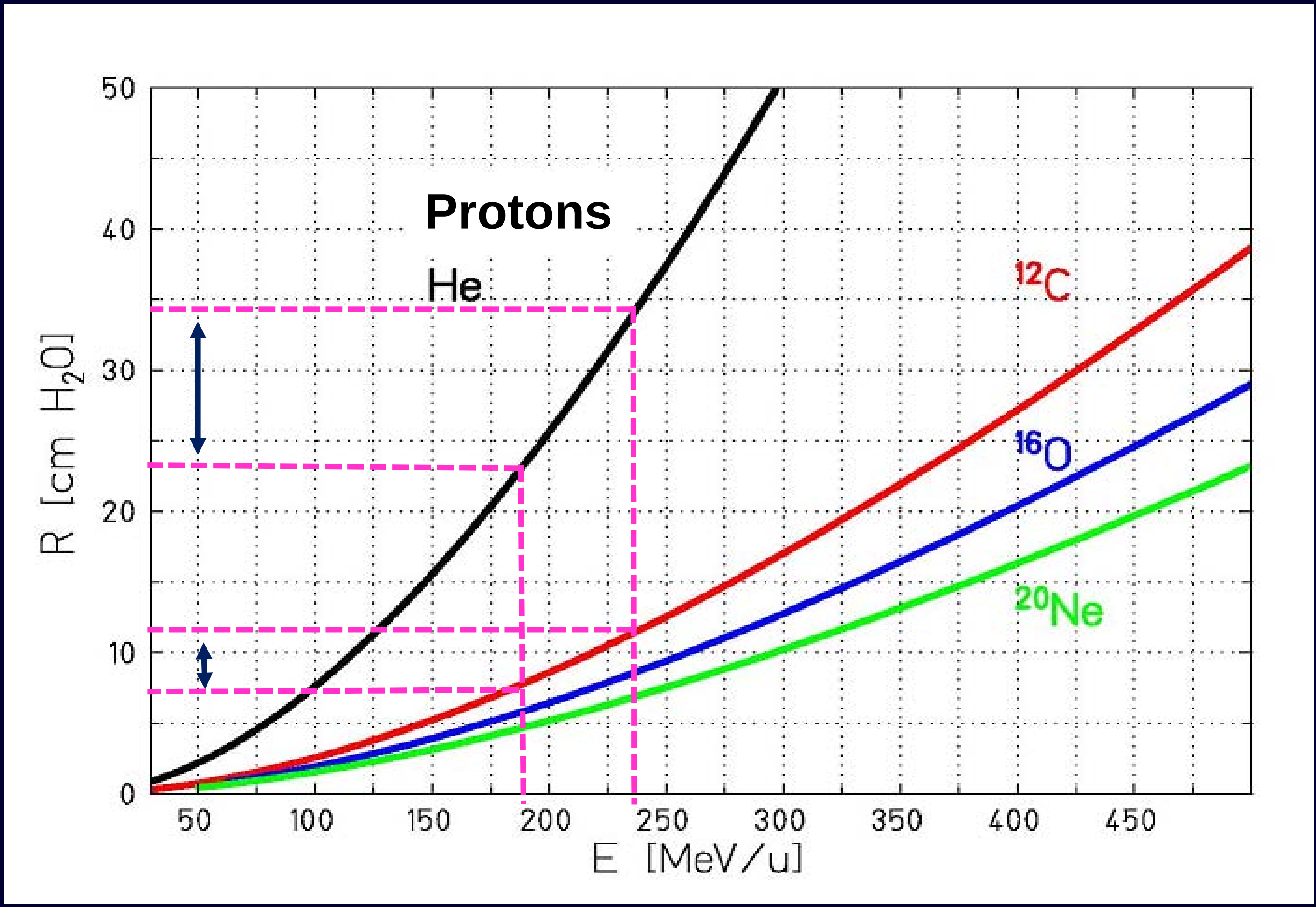
$$\frac{dE}{dx} = \frac{4\pi e^4}{m_e} \frac{z^2}{v^2} NZB$$

$B = \ln(2m_0V^2) - \ln(I(1-\beta^2)) - \beta^2$

Where:
E = instantaneous total energy of the particle
e = electron charge
m_e = electron mass
v = Particle Speed
ze=Charge of the Particle
Z= Atomic Number of the absorbing material
N=#atoms/cubic cm of the absorbing material

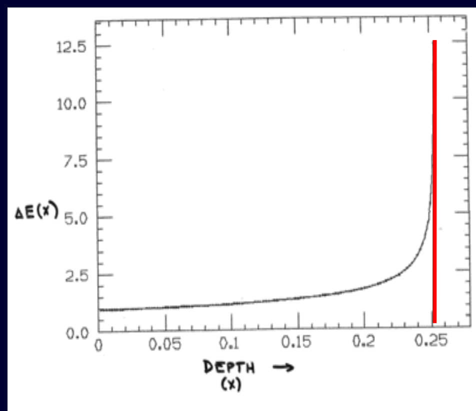
Ions with higher charge or lower speed lose energy faster

Particle Range vs Energy

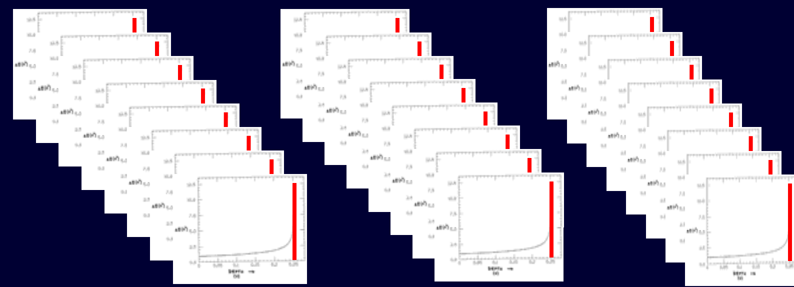


Bragg Peak

A Single Proton

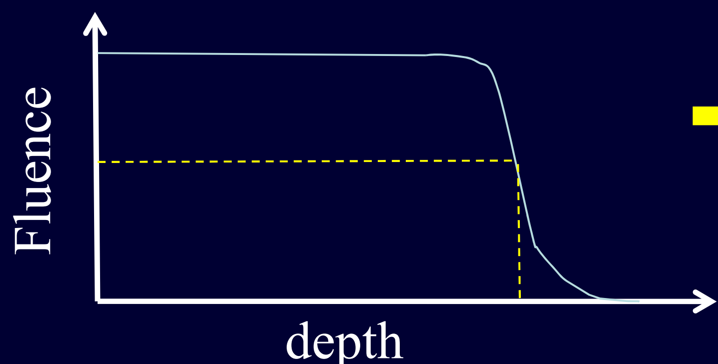


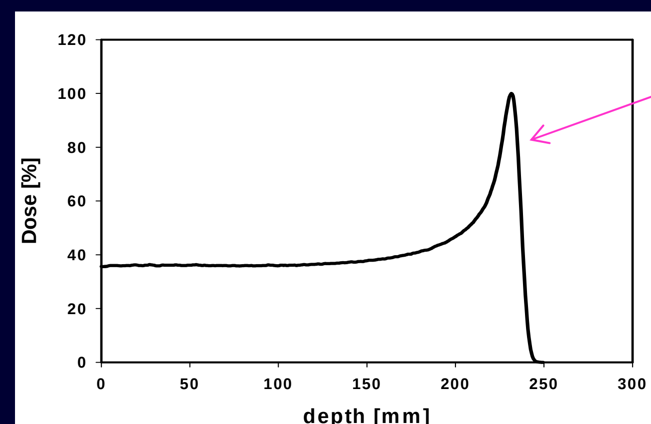
Many Protons



Each has different number of interactions
Loses different amount of energy each time

Protons stop at different depths



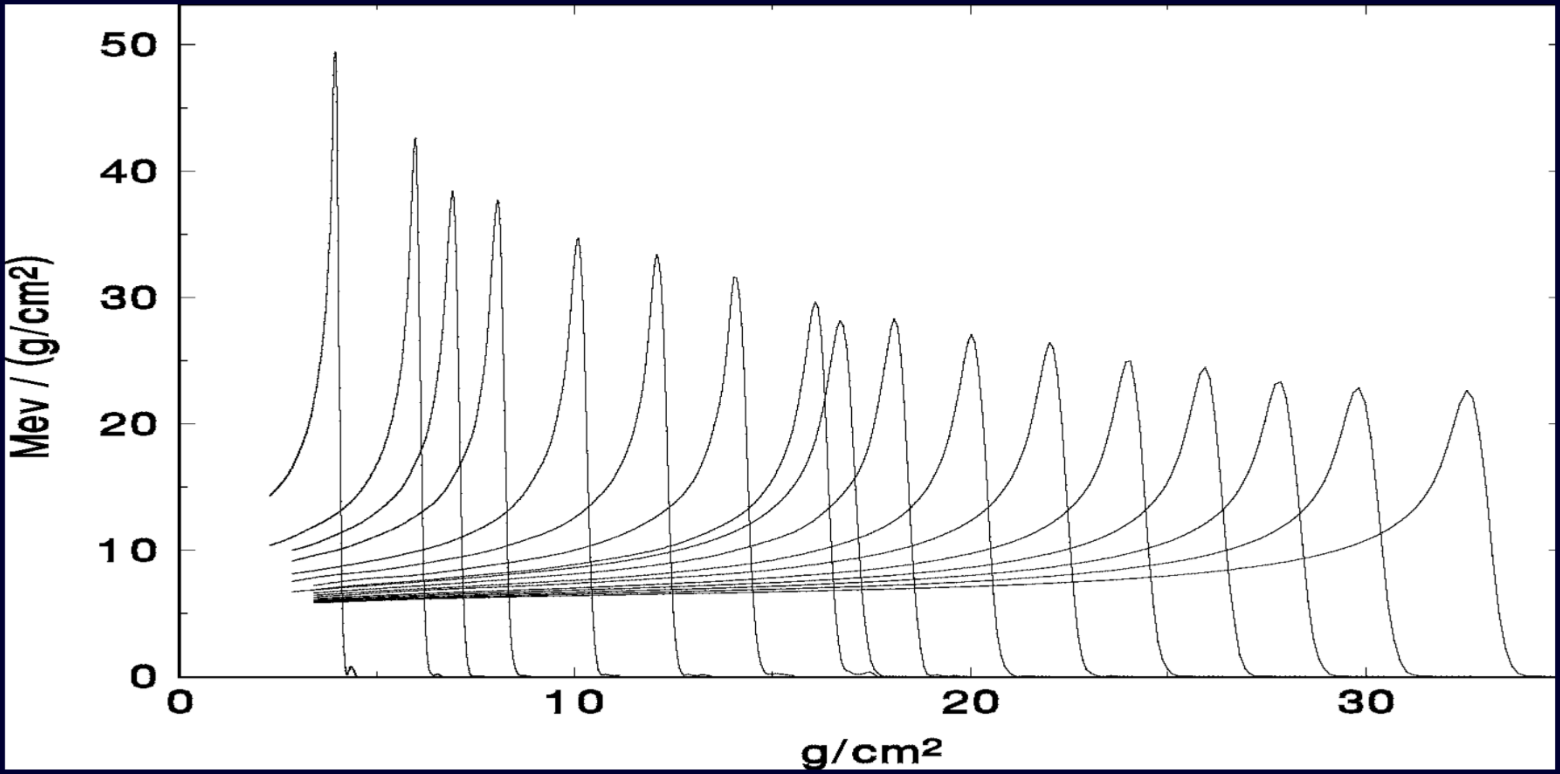


Beam range @80% or 90%

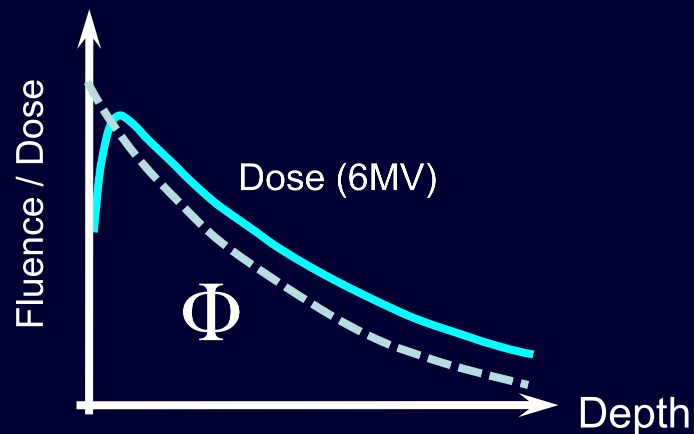
Total Dose Distribution in Depth

Range Straggling

Energy spread increases with depth of penetration
Low energy beams have narrower Bragg peaks

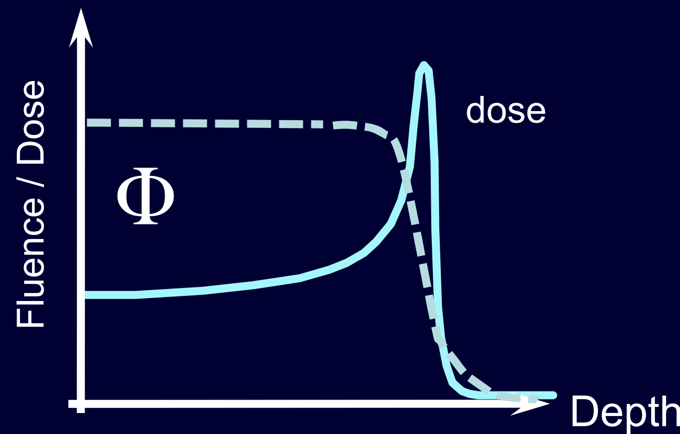


Dependence on Depth



Photons:

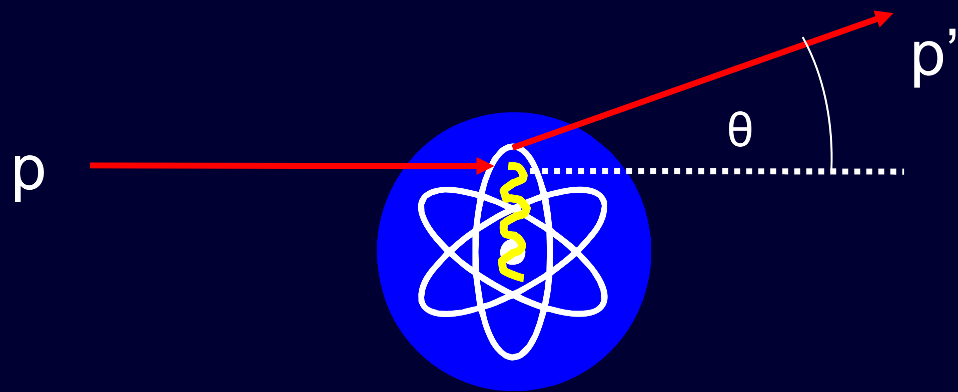
- Attenuation, fluence decreasing
- No substantial change in photon energy spectrum
- No change in electron energy spectrum from Compton scattering
- No change in ratio between biological dose and physical dose
- Compton electron energies mostly high → dose buildup near surface



Particles:

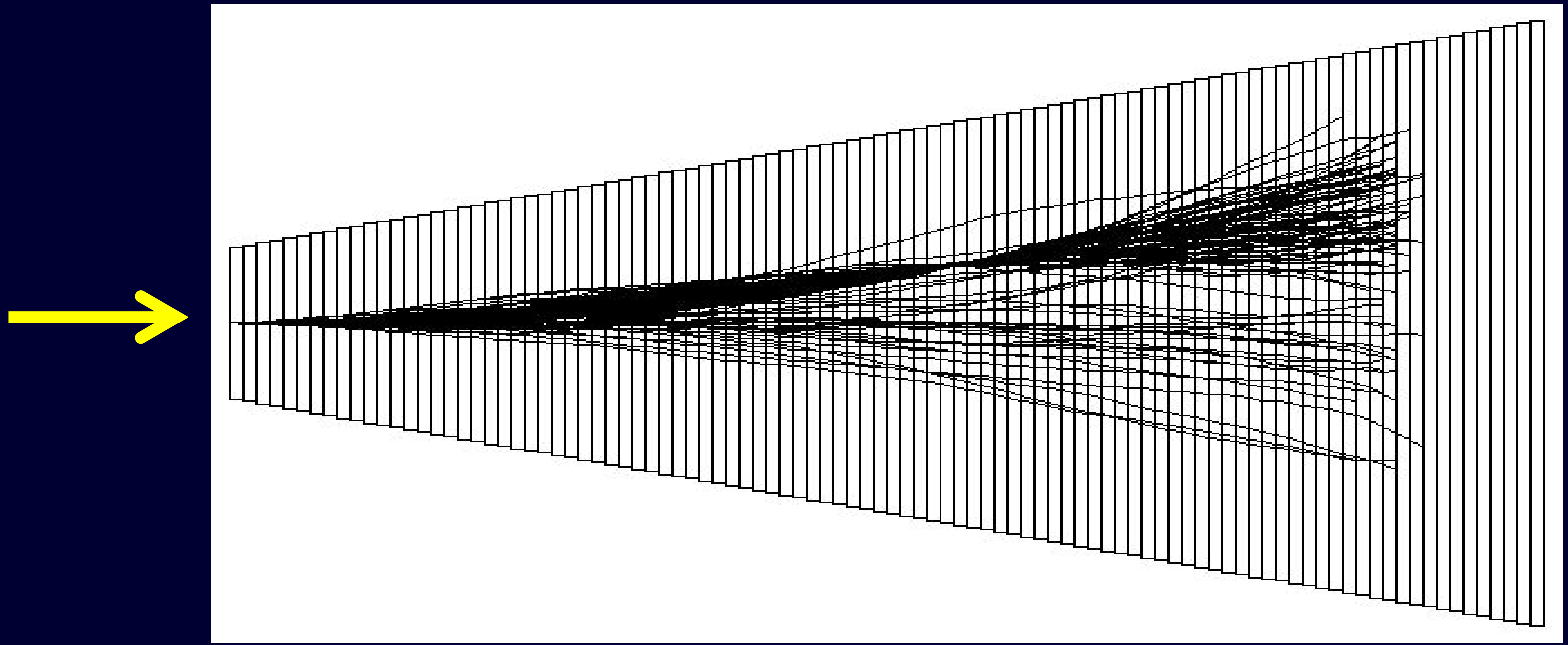
- No attenuation, fluence stays constant except near the end
- Particles lose energy gradually
- Energy loss per ion pair stays same
- Ion pairs per unit length increases
- Increase in LET, and possibly in ratio between biological dose and physics dose, i.e., increase in RBE
- Electron energy low → no buildup

Multiple Coulomb Scattering



- Protons are deflected in the electric field of the nuclei.
- In general, multiple deflections will occur for each proton
- Play key role in determining lateral dose distribution

MCS Simulated

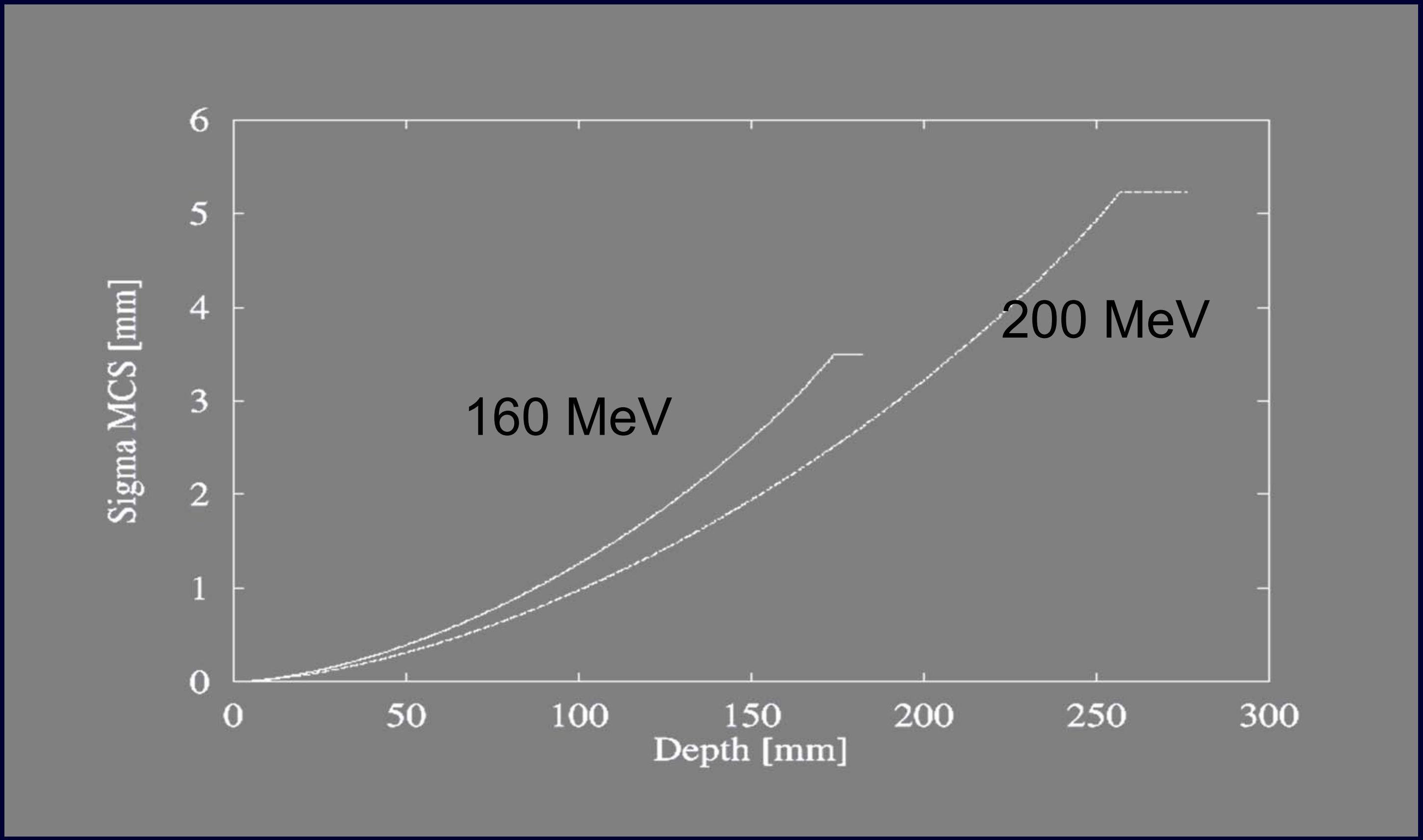


Mono-energetic incident protons

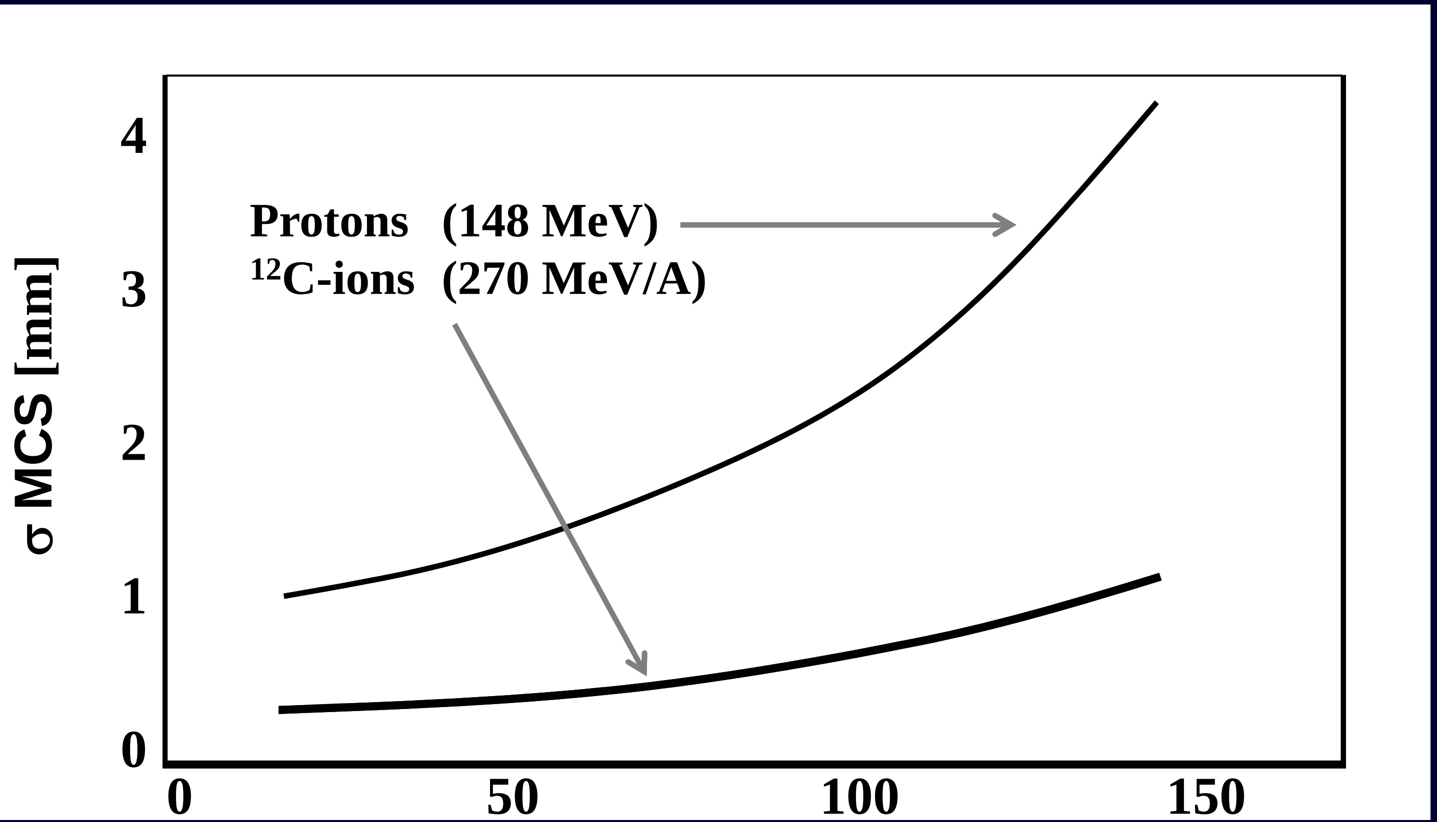
(Transverse scale greatly exaggerated)

Adapted from Gottschalk

MCS Dependence on Beam Energy

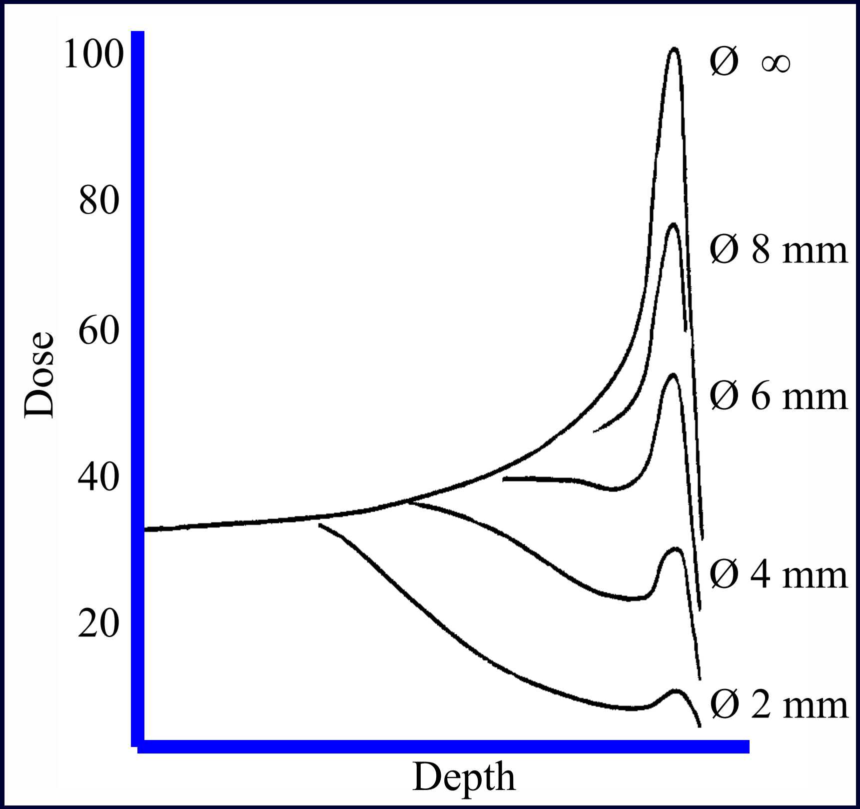


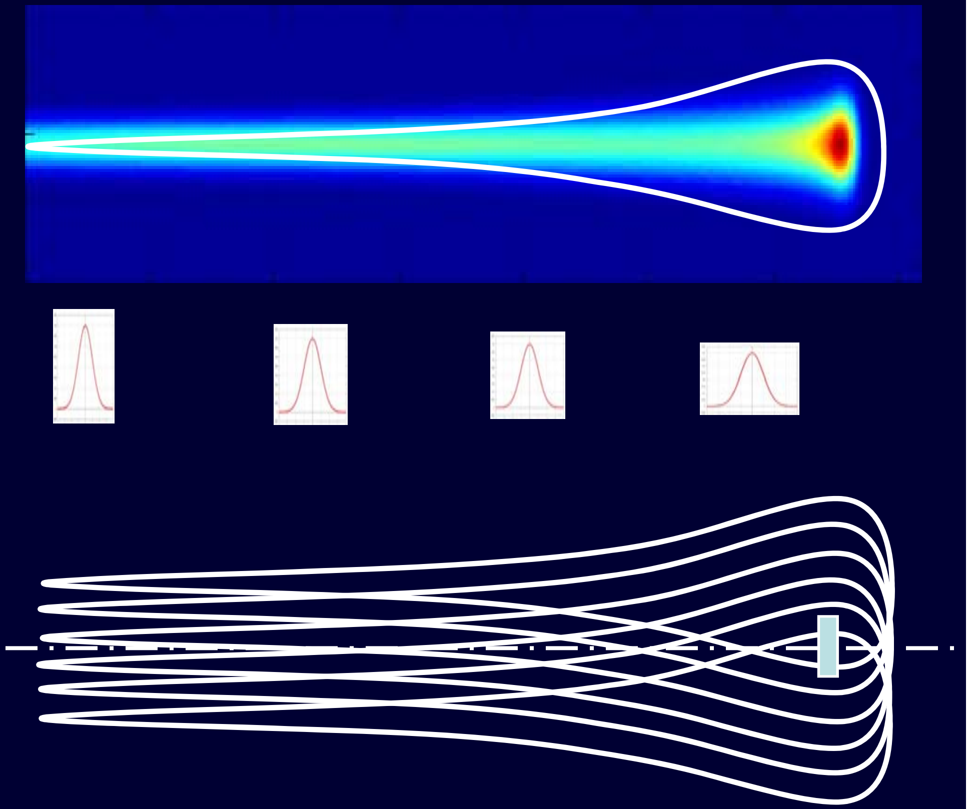
MCS Dependent on Particle Mass



Depth [mm]

The Loss of Bragg Peak





Adapted from Gottschalk

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Lateral Penumbra Changes in Depth

Photons:

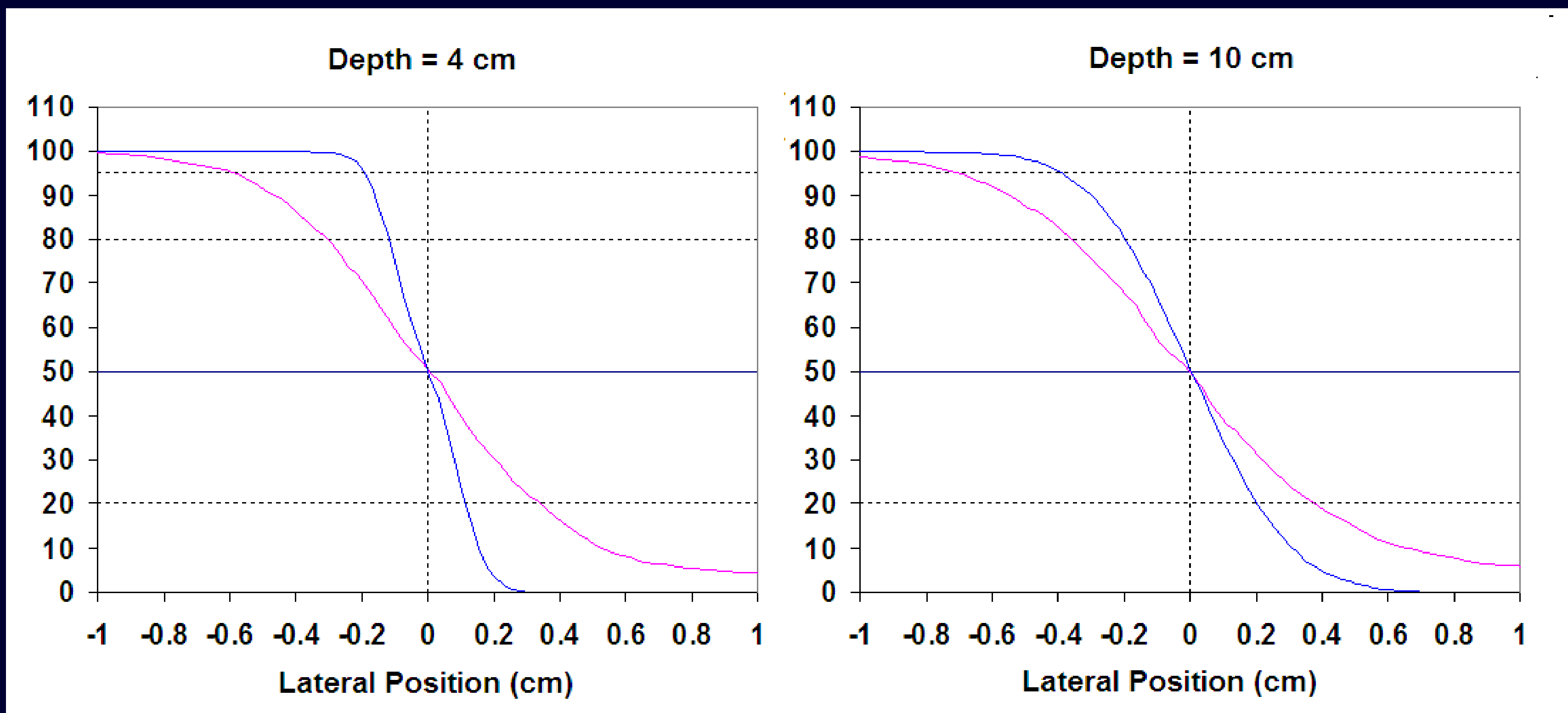
- Some photons interact with electrons by Compton scattering
- Scattered photons get out of beam
- Remaining photons have almost same energy spectrum
- No change over depth in the energy and momentum distribution of the electrons from Compton scattering
- Therefore no change in lateral buildup situation in terms of dose
- Intrinsic penumbra unchanged
- Penumbra changes in depth mainly affected by source size and location.

Particles:

- Particles experiences MCS
- Each time deflected by a small angle, but the particle stays in the beam
- Effect of deflection accumulates.
- Particles spread out laterally. Gaussian flattens out
- Beam penumbra increases
- At the same time, particle energy decreases and deflection angle increases for each interaction.
- Beam penumbra increases faster near the end of beam range.

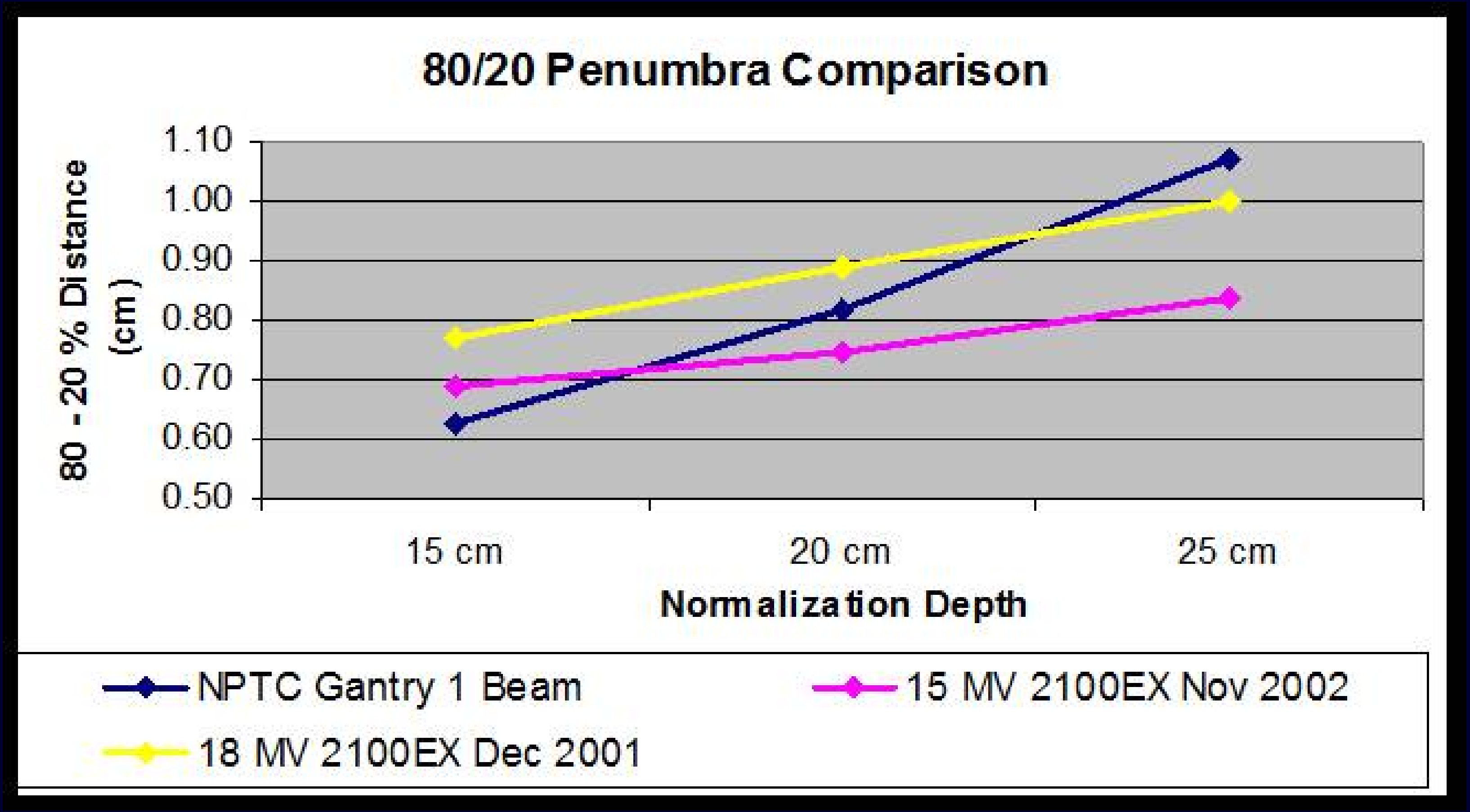
Lateral Penumbra Comparison

Photon (6 MV) vs Proton (Range 14 / Mod 10 cm)

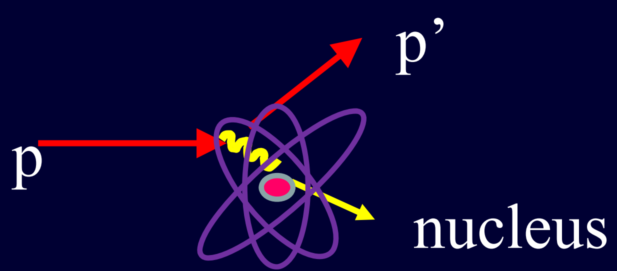


Proton Penumbra Advantage

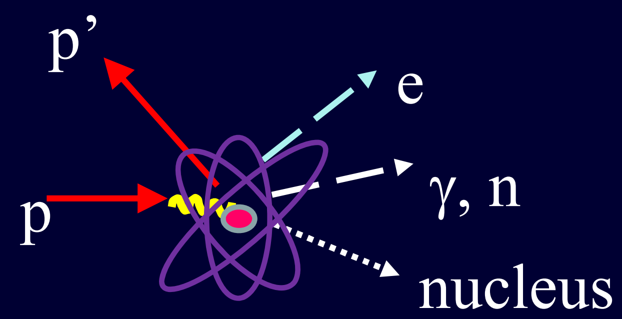
- Up to 18 cm …



Nuclear interactions of protons



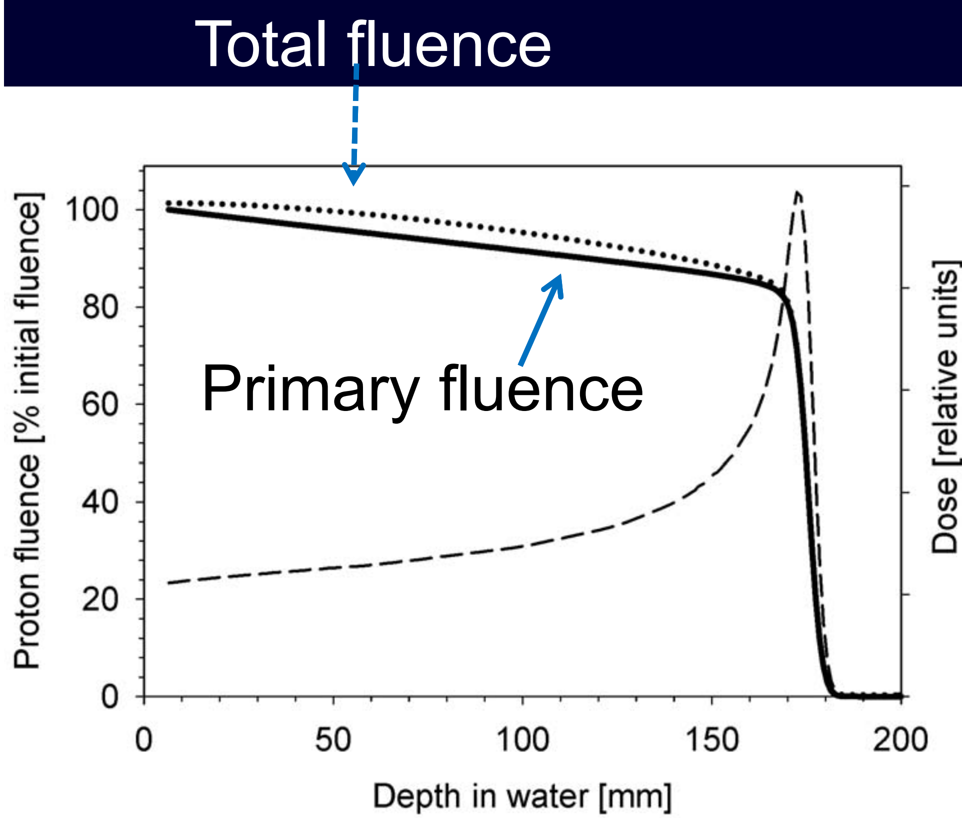
Elastic collision (large θ)

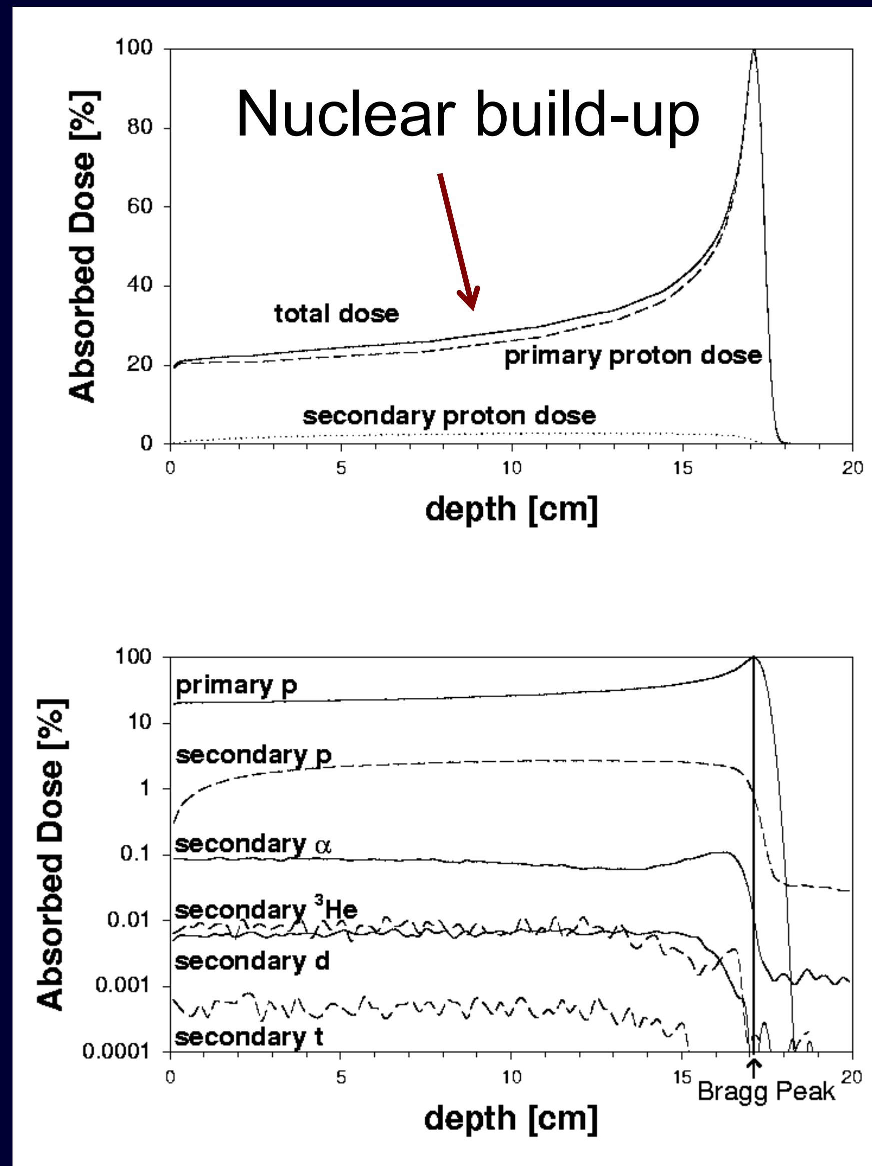


Nuclear interaction

- A certain fraction of protons have nuclear interactions in tissue (about 1% of all protons per cm of penetration)
- Mostly with oxygen and carbon nucleus
- Nuclear interactions cause a decrease in primary proton fluence
- Nuclear interactions lead to secondary particles and thus to local and non-local dose deposition (neutrons!)
- The dose from nuclear interactions is negligible in the Bragg peak

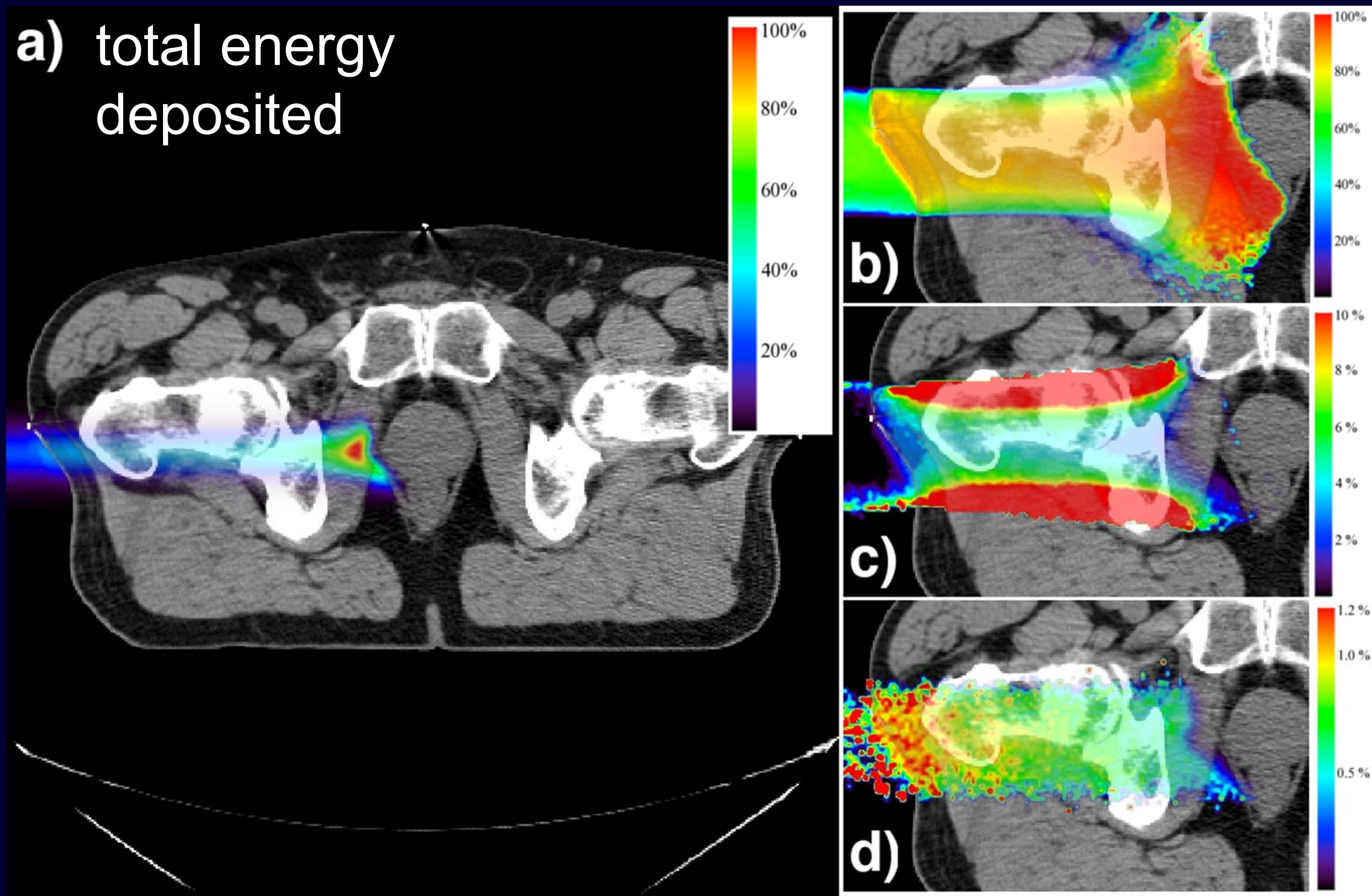
Dose by Nuclear Interactions





Spatial Distribution

Contribution in %

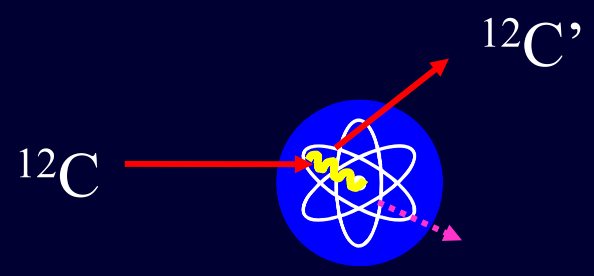


primary protons

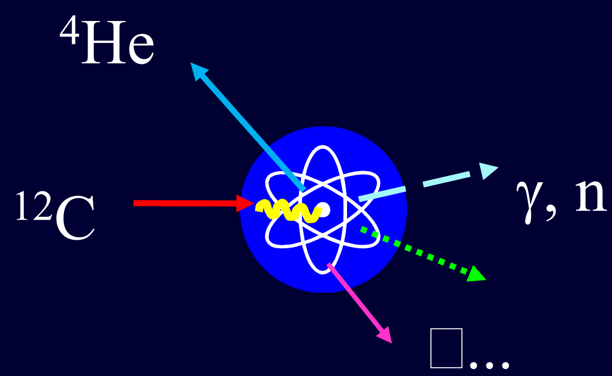
secondary protons

alphas & recoils

Nuclear interactions of heavy ions

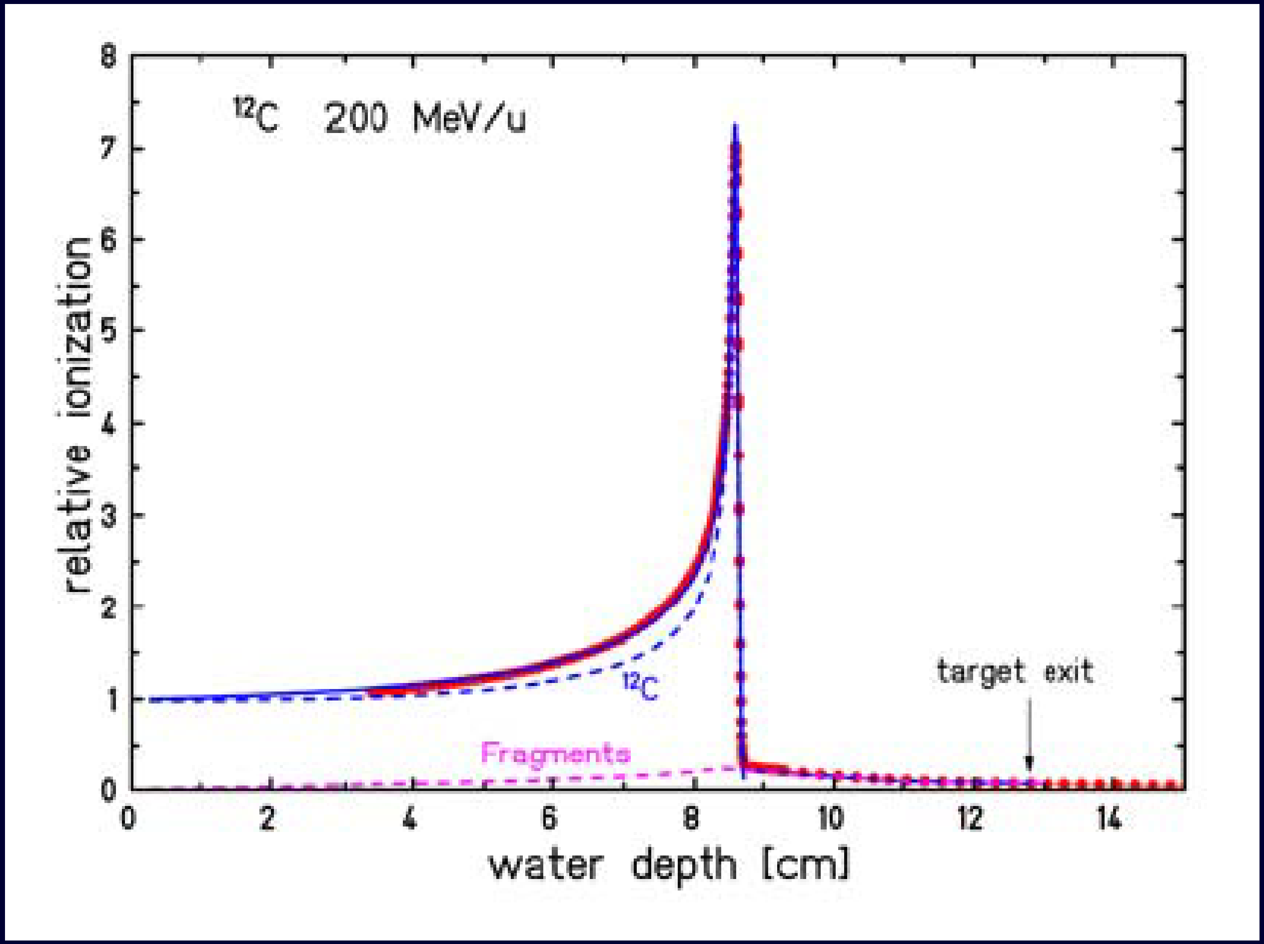


Elastic nuclear collision (large θ)



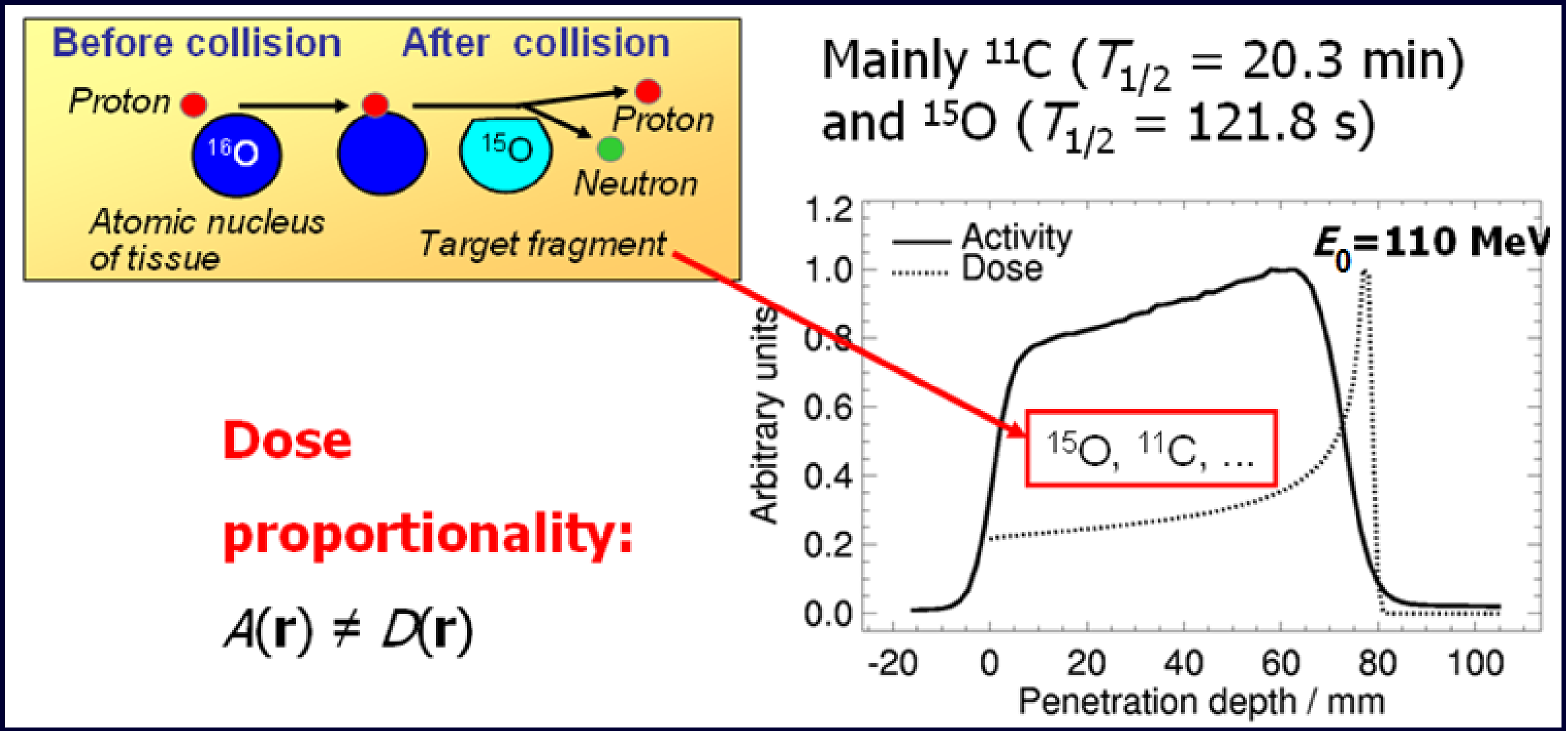
Nuclear interaction (fragmentation)

Dose Contribution from Fragmentation



In-vivo Dose Verification with PET

- Protons and heavy ions cause nuclear fragmentation reactions
- Products include positron emitting isotopes (^{15}O, ^{11}C)
- PET scan measures distribution of activities
- Activity distribution related to dose distribution



Take Home Messages

- Heavy charged particles interact with matter very differently from photons
- The unique characteristics of the ionization process create the Bragg peak dose distribution
- Particle beams offer potential variation of biological effectiveness in depth (LET increase)
- Multiple Coulomb scattering causes broader lateral beam penumbra at deeper depth
- Heavy charge particles cause inelastic nuclear interactions and produce neutrons