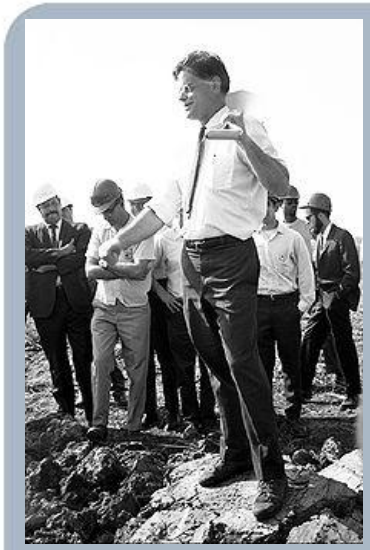
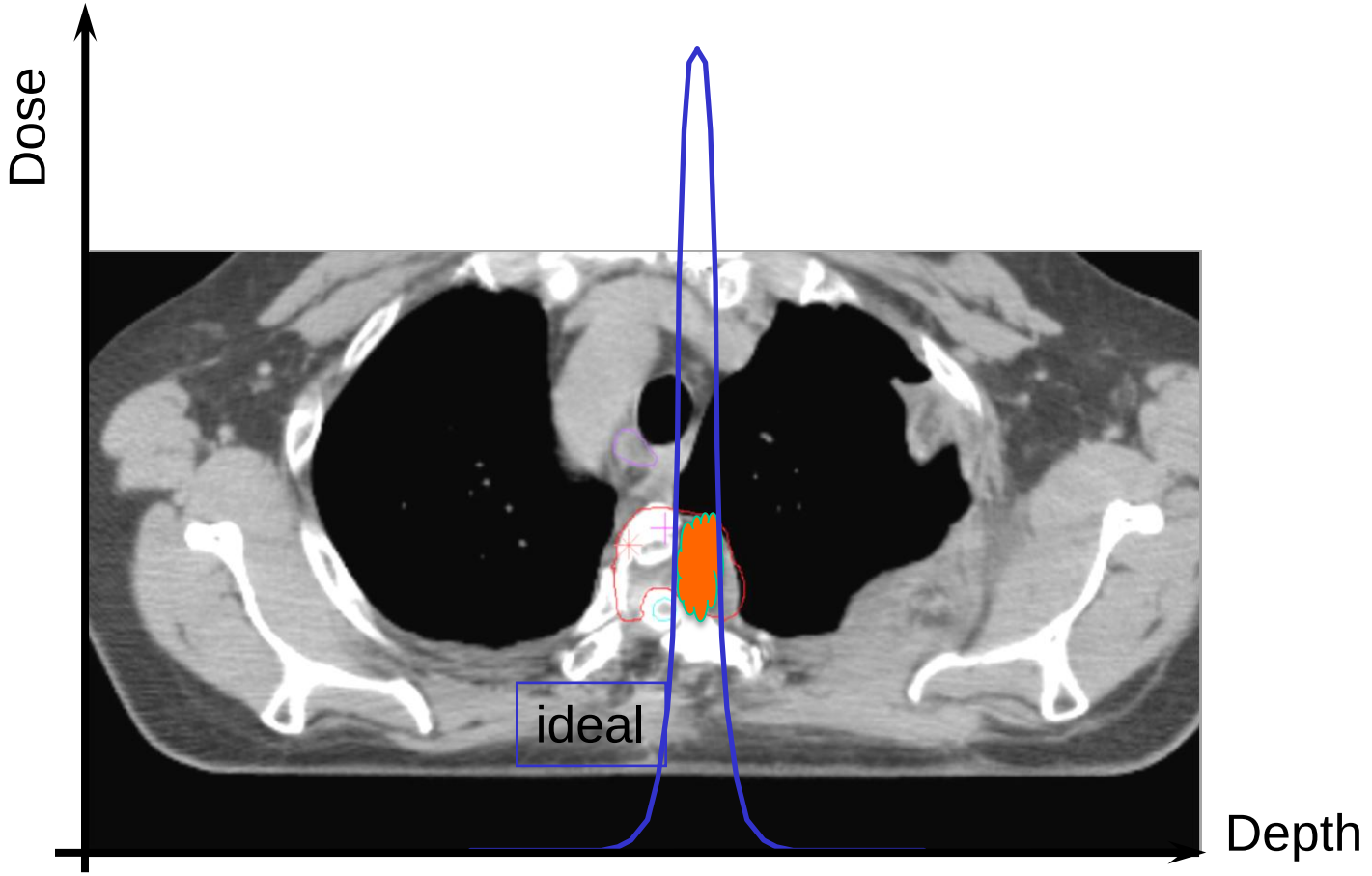


Physics of particles

H. Paganetti PhD

Massachusetts General Hospital & Harvard Medical School

The ideal dose distribution

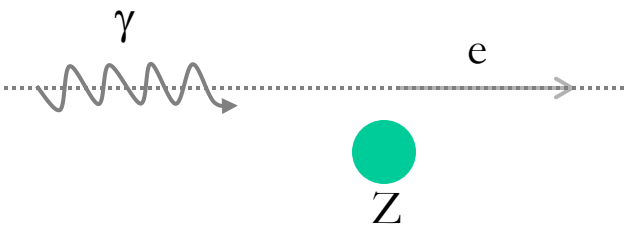


Dose: **Energy deposited** **Energy/Mass** **[J/kg] [Gy]**

Introduction

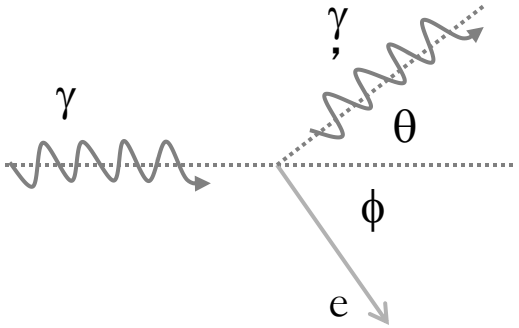
Photoelectric Effect

Photon ejects electron from an atom.



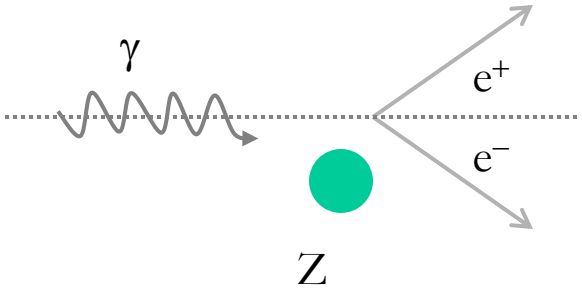
Compton Effect

Photons scattering from atomic electrons.

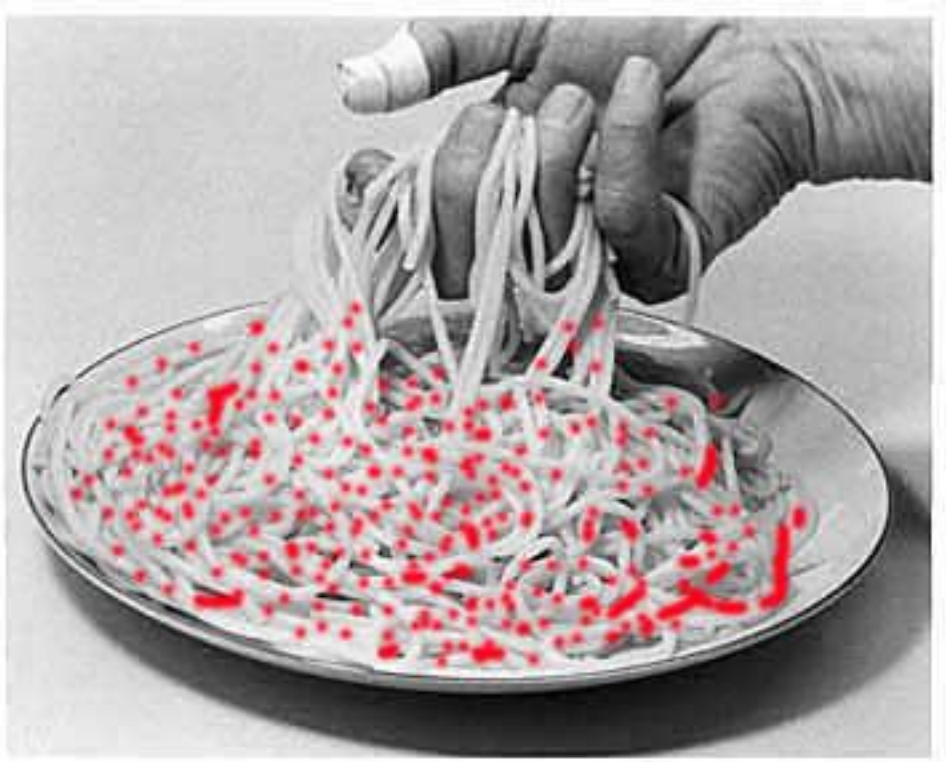


Pair Production

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

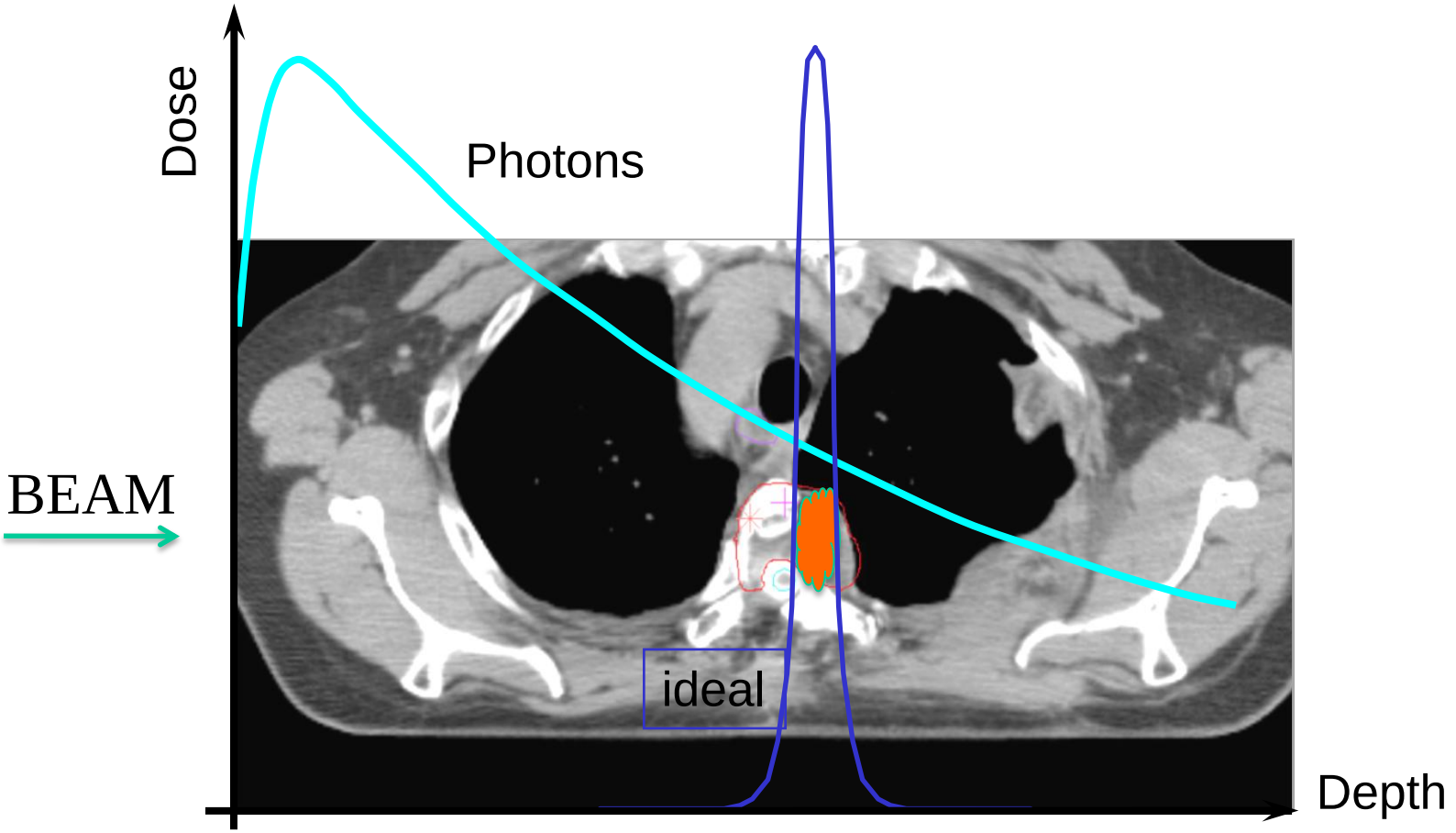


Dose deposition

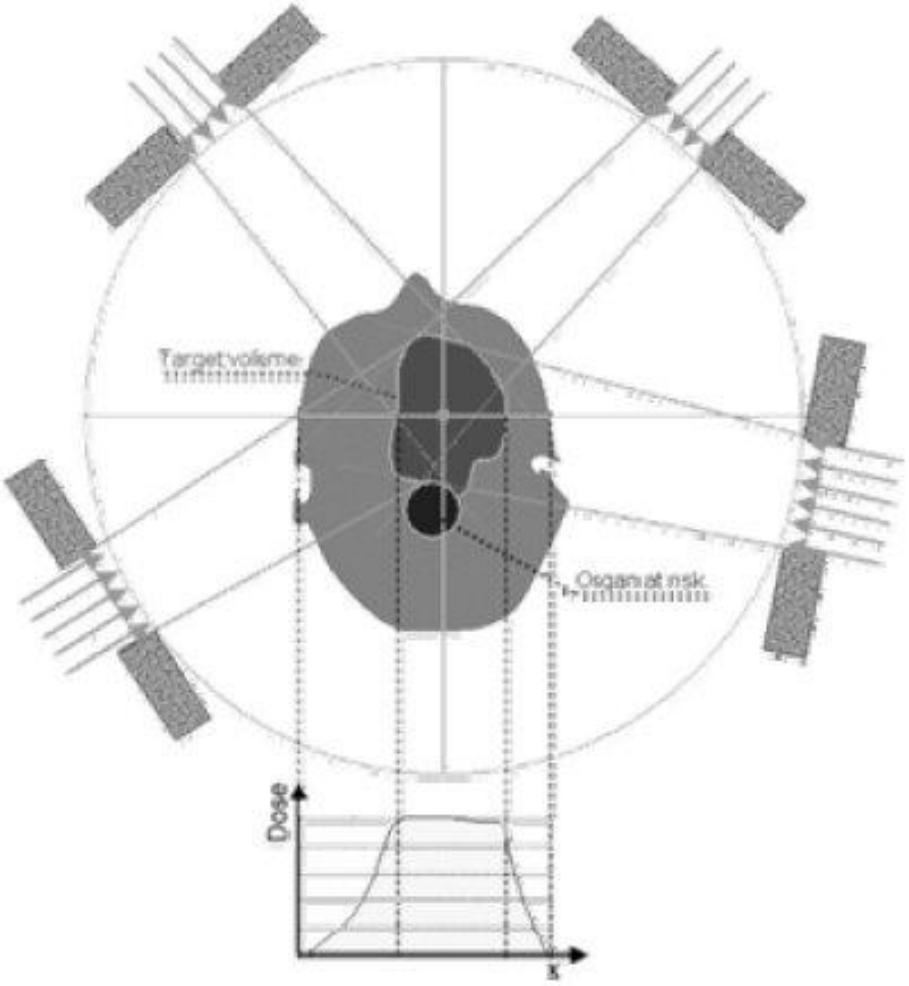


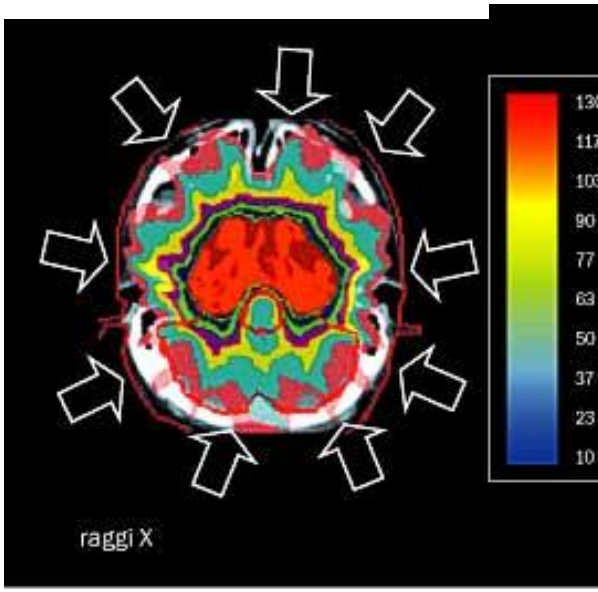
Electrons

Introduction



Use of multiple beams (different directions)





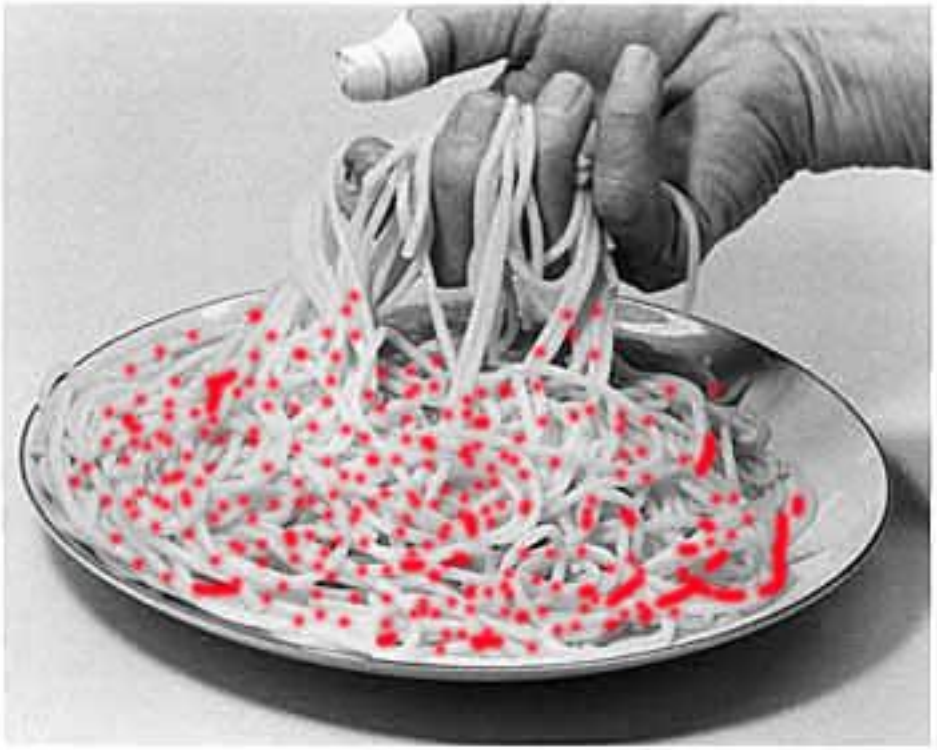
Also:
Modulation of intensities

Introduction

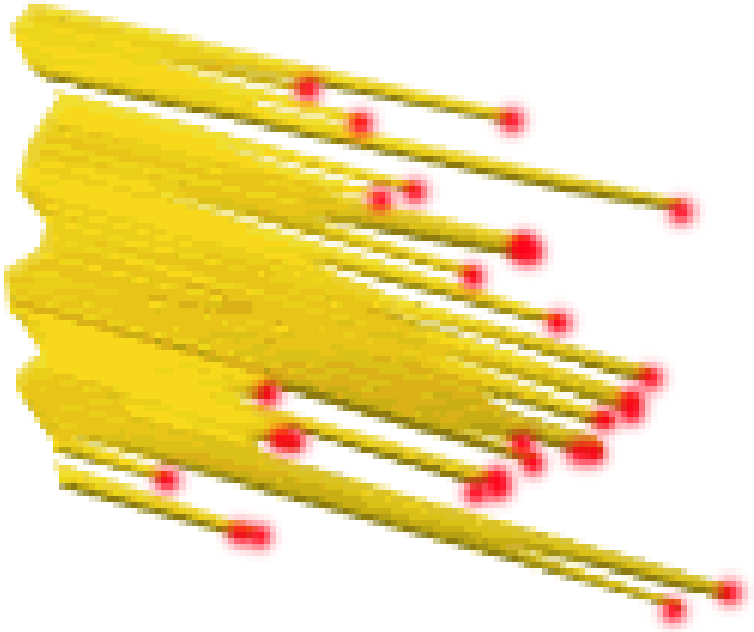
- Photons
  - Charge: 0
  - Indirect Ionization
- Electrons
  - Charge: -1
  - Direct Ionization
  - Mass: 512 keV

- Protons
  - Charge: +1
  - Direct Ionization
  - Mass: 2,000 • m_e

Dose deposition

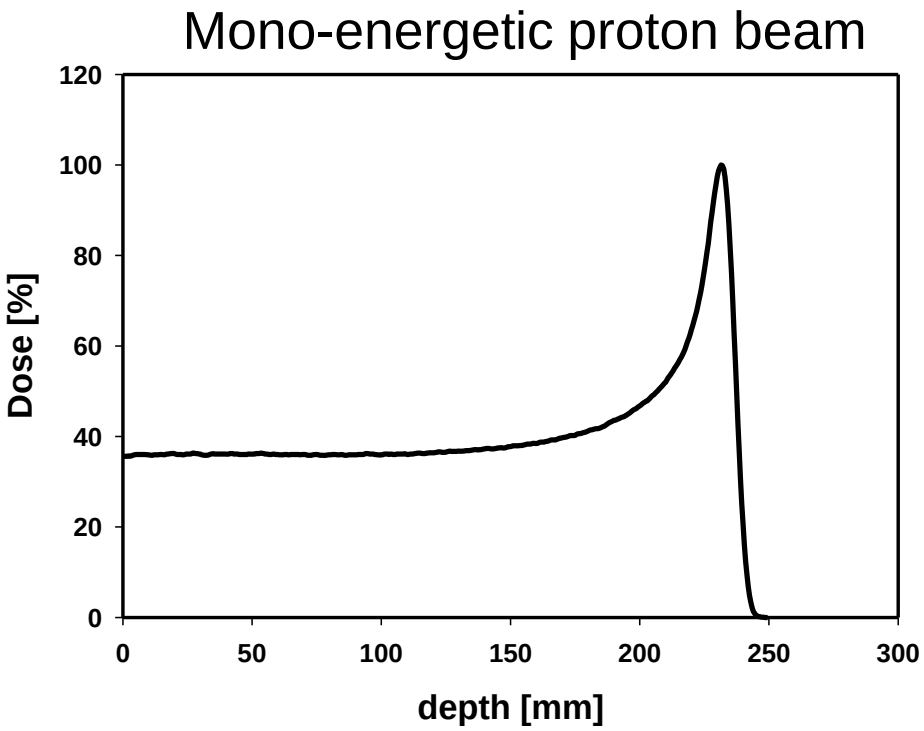


Electrons

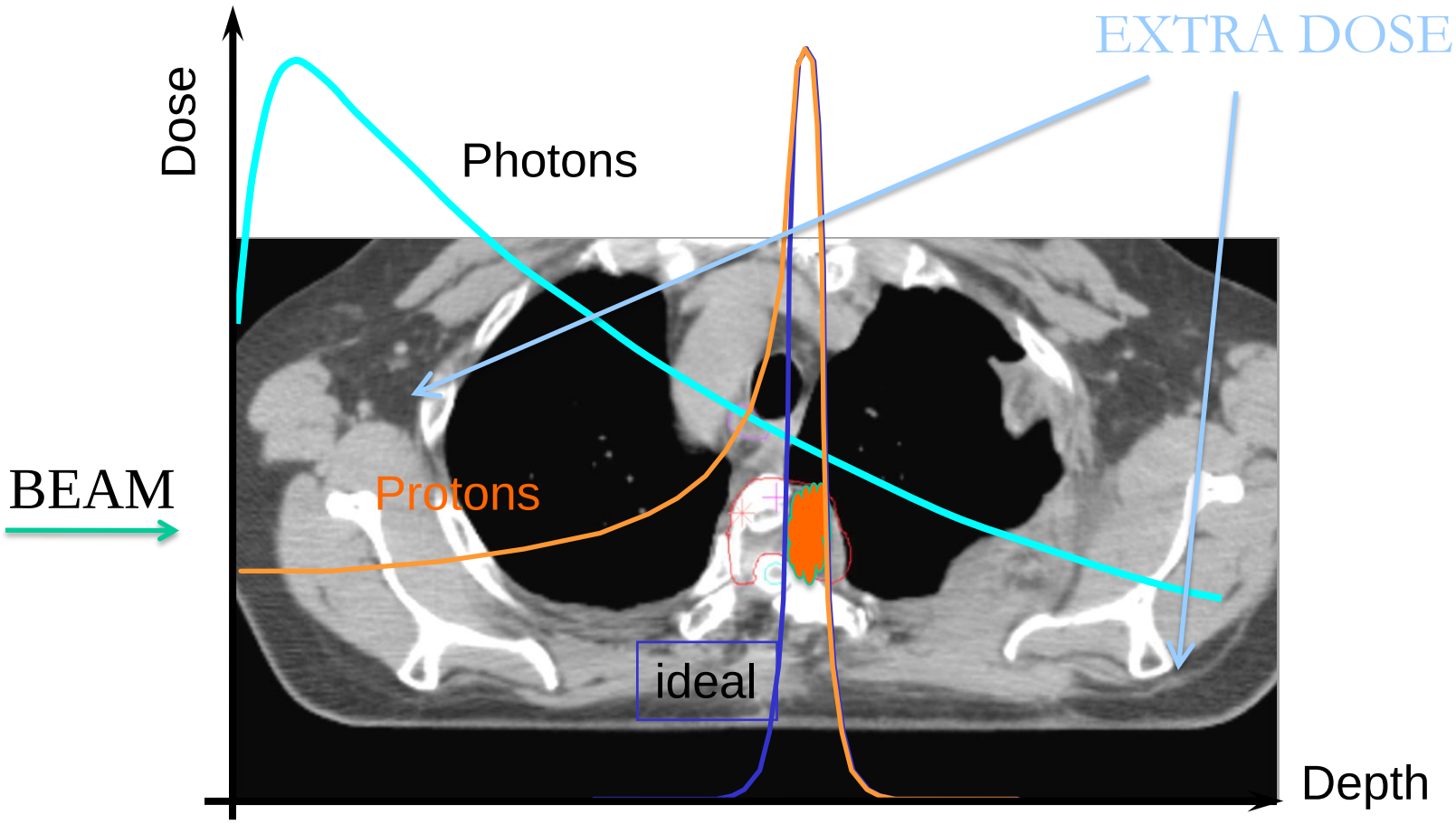


Protons

The Bragg curve

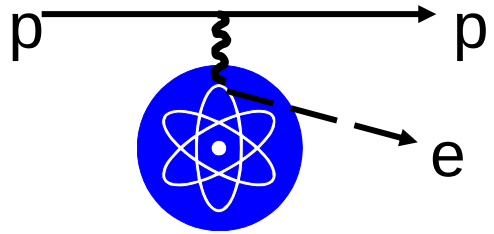


Introduction

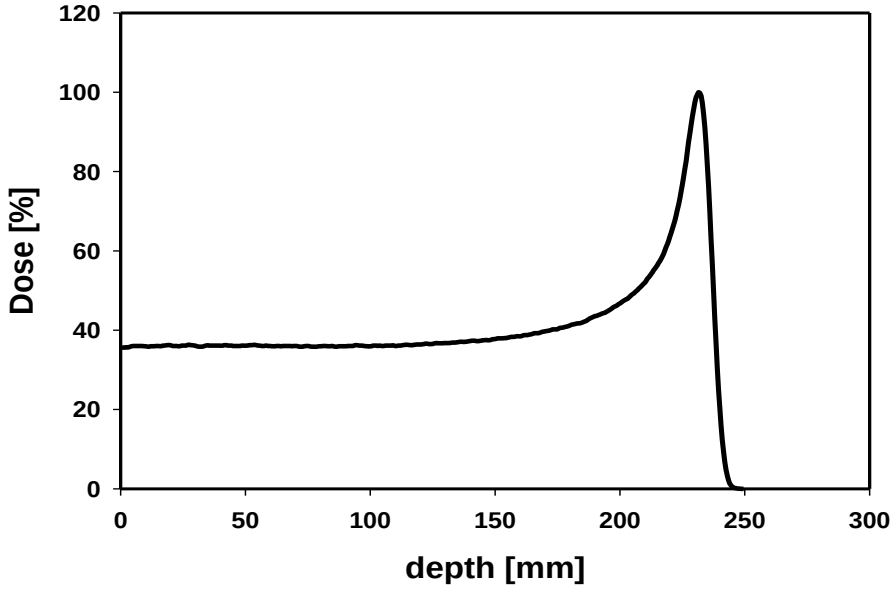


Beam energy controls the range

Electromagnetic energy loss of protons



- Distal distribution
  - –Ionization
  - –Excitation



Interaction probability is proportional to proton energy

Bethe-Bloch equation

$$\left(\frac{dE}{dx}\right)_0 = \frac{2\pi n_e r_e^2 m_e c^2 z^2}{\beta^2}\left[\ln\left(\frac{2m_e c^2 \beta^2 T_{\max}}{I^2(1-\beta^2)}\right) - 2\beta^2 + 2zL_1(\beta) + 2z^2 L_2(\beta) - 2\frac{C}{Z} - \delta + G\right]$$

- I : mean excitation energy , material-dependent
- δ : density correction
- C : is the shell correction, important at low energies
- T_{max} : maximum energy transfer to an electron
- L_1 : Barkas correction (z^3)
- L_2 : Bloch (z^4) correction
- G : Mott corrections

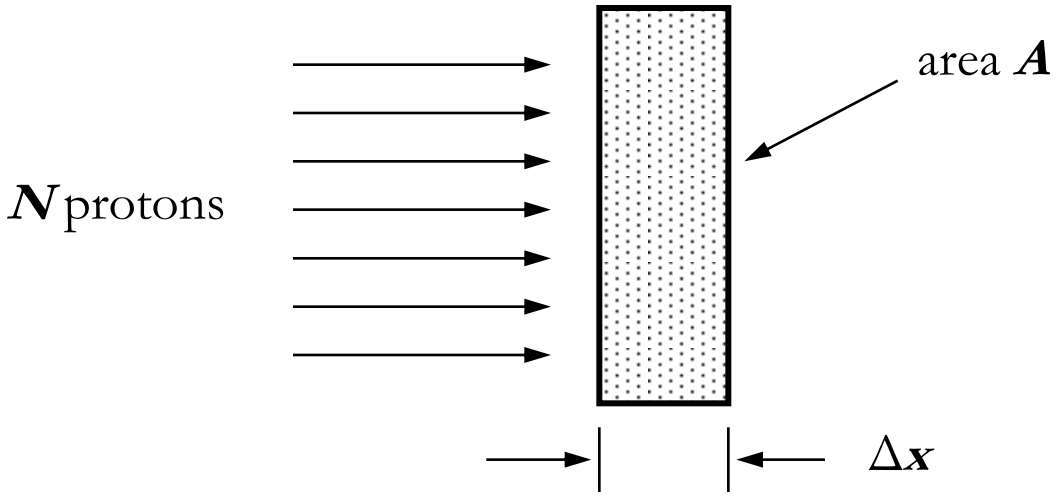
Bethe [-Bloch] equation

$$-\frac{dE}{dx} = \frac{4\pi nk^2 Z^2 e^4}{mc^2 b^2}\left[\ln\frac{2mc^2 b^2}{I(1-b^2)} - b^2\right]$$

$\beta = v/c$

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

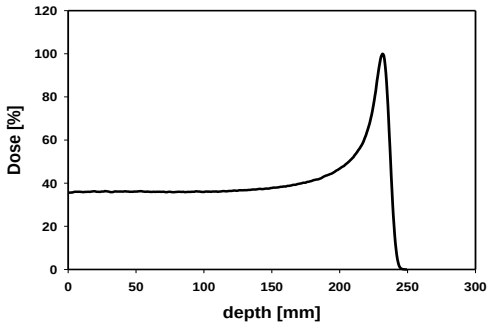
Protons/Ions – Basic Physics

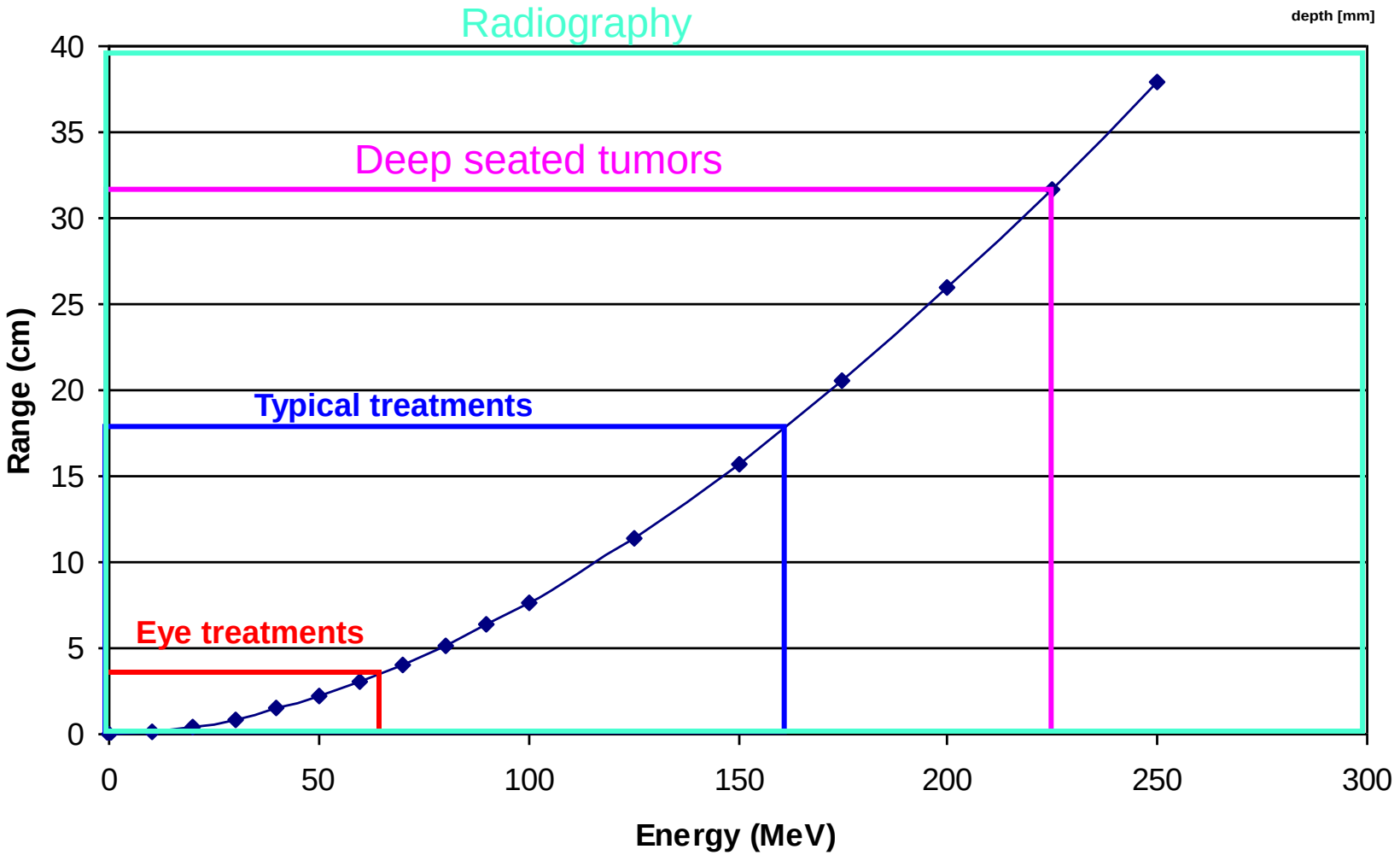


$$D \equiv \frac{\text{energy}}{\text{mass}} = \frac{(dE/dx) \times \Delta x \times N}{\rho \times A \times \Delta x} = \Phi \frac{S}{\rho}$$

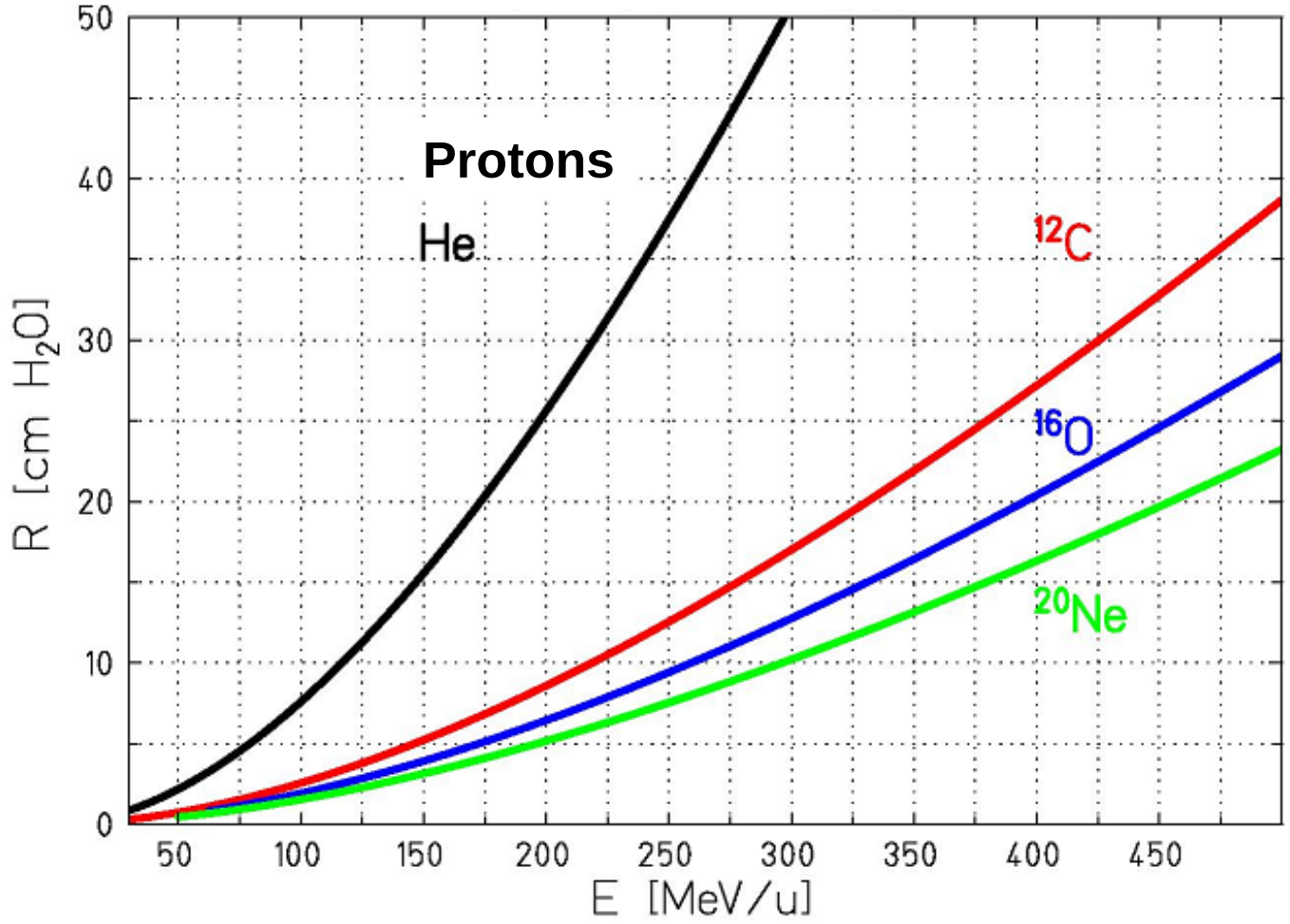
Dose = fluence × mass stopping power

Protons/Ions – Basic Physics

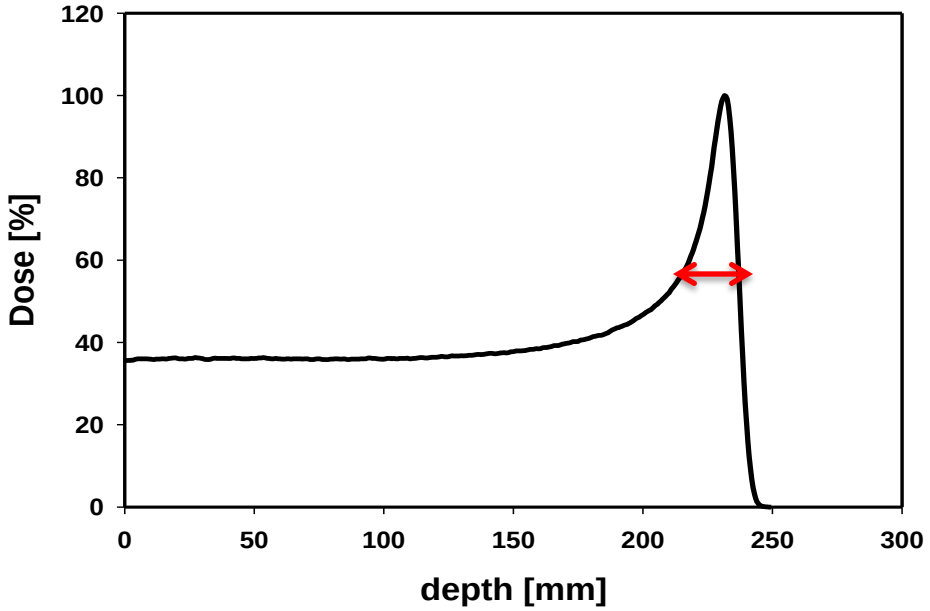




Protons/Ions – Basic Physics

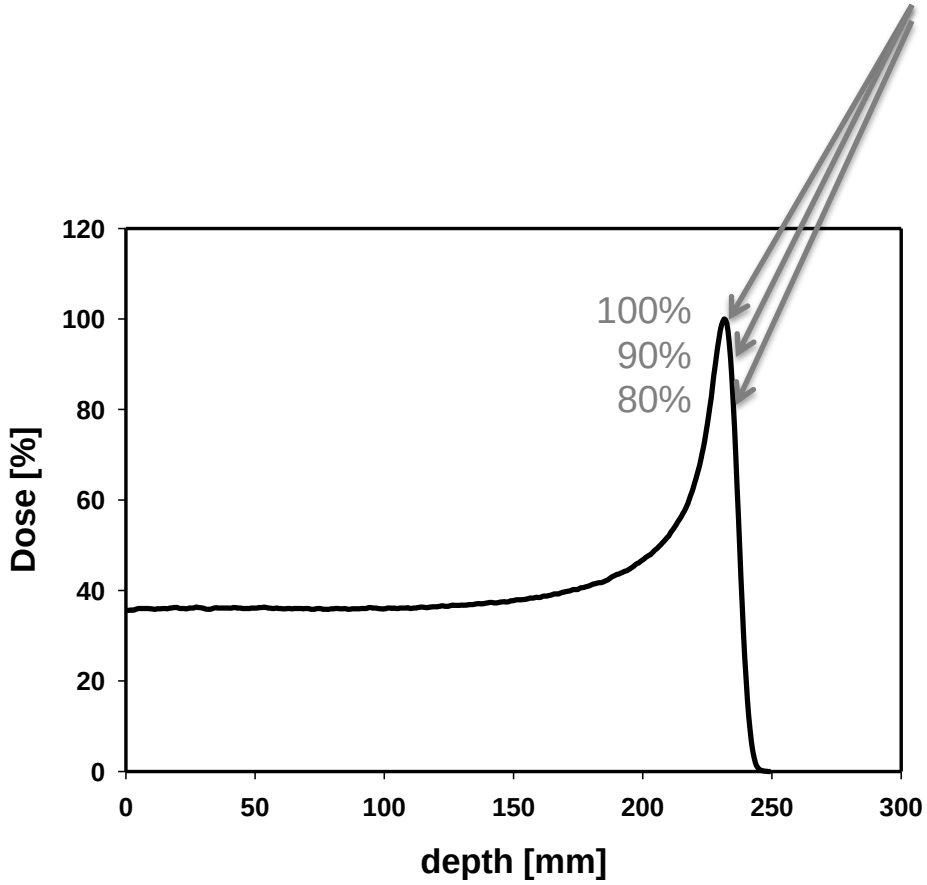


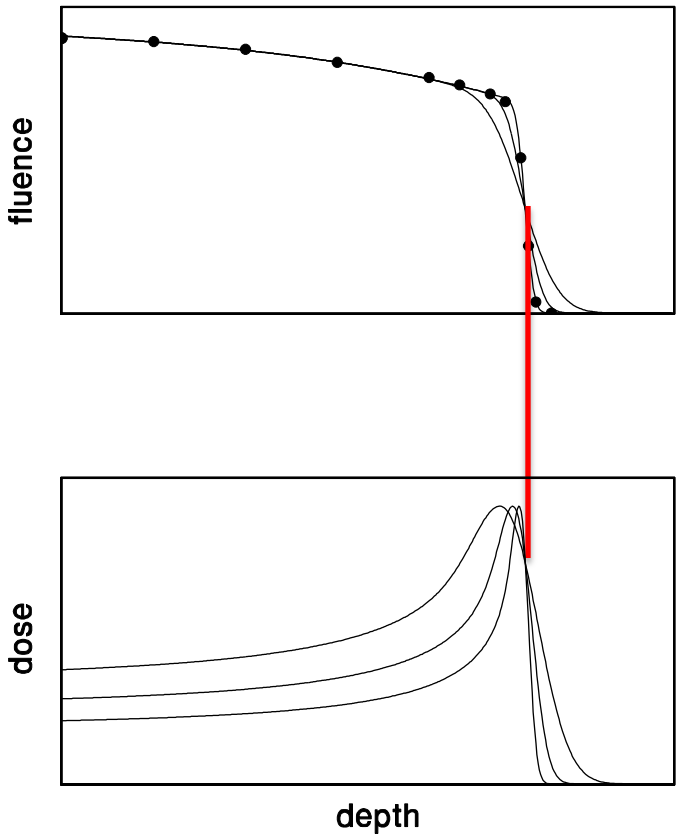
Protons/Ions – Basic Physics



- Protons lose their energy in individual collisions with electrons
- Protons with the same initial energy may have slightly different ranges:
  "Range straggling"

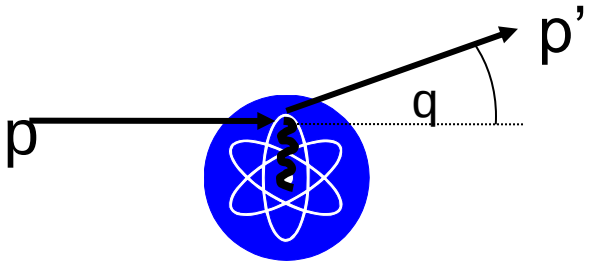
Beam Range



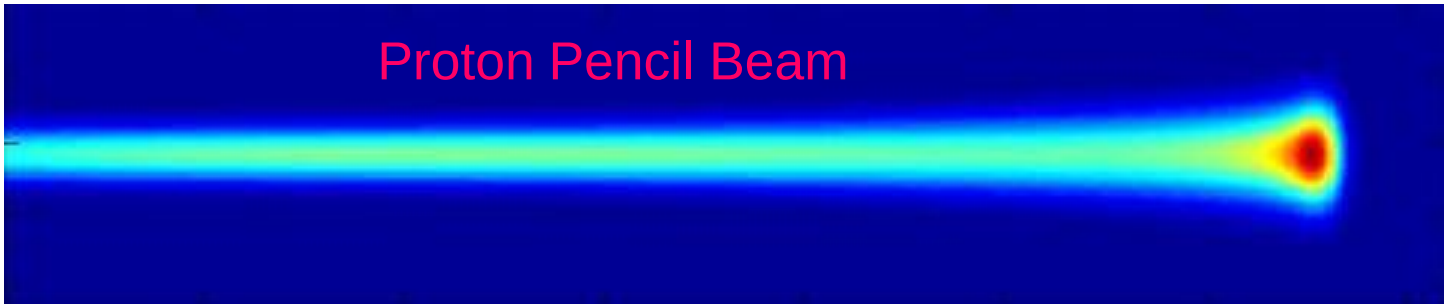


Electromagnetic energy loss of protons

- Lateral distribution



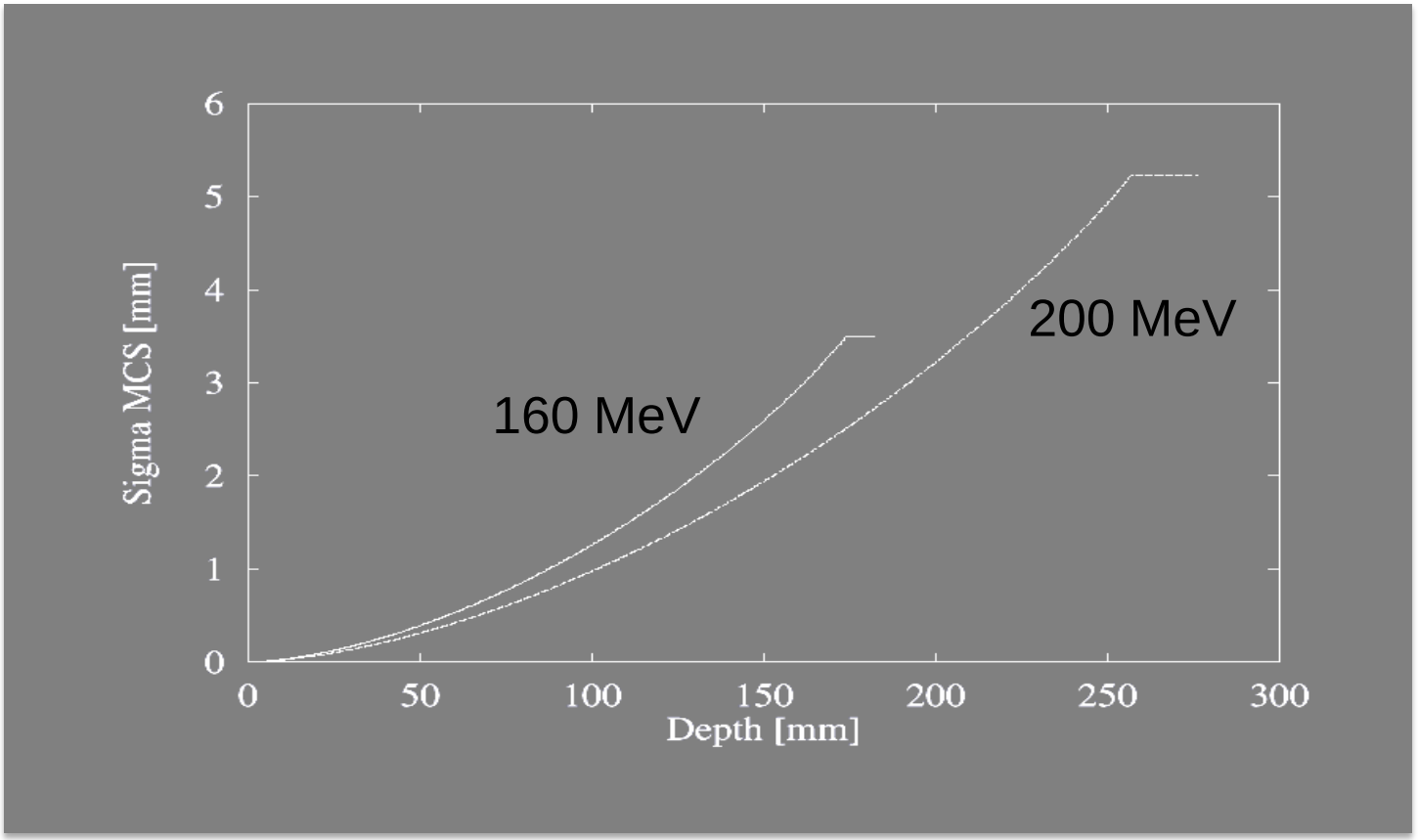
Multiple Coulomb scattering (small angles)



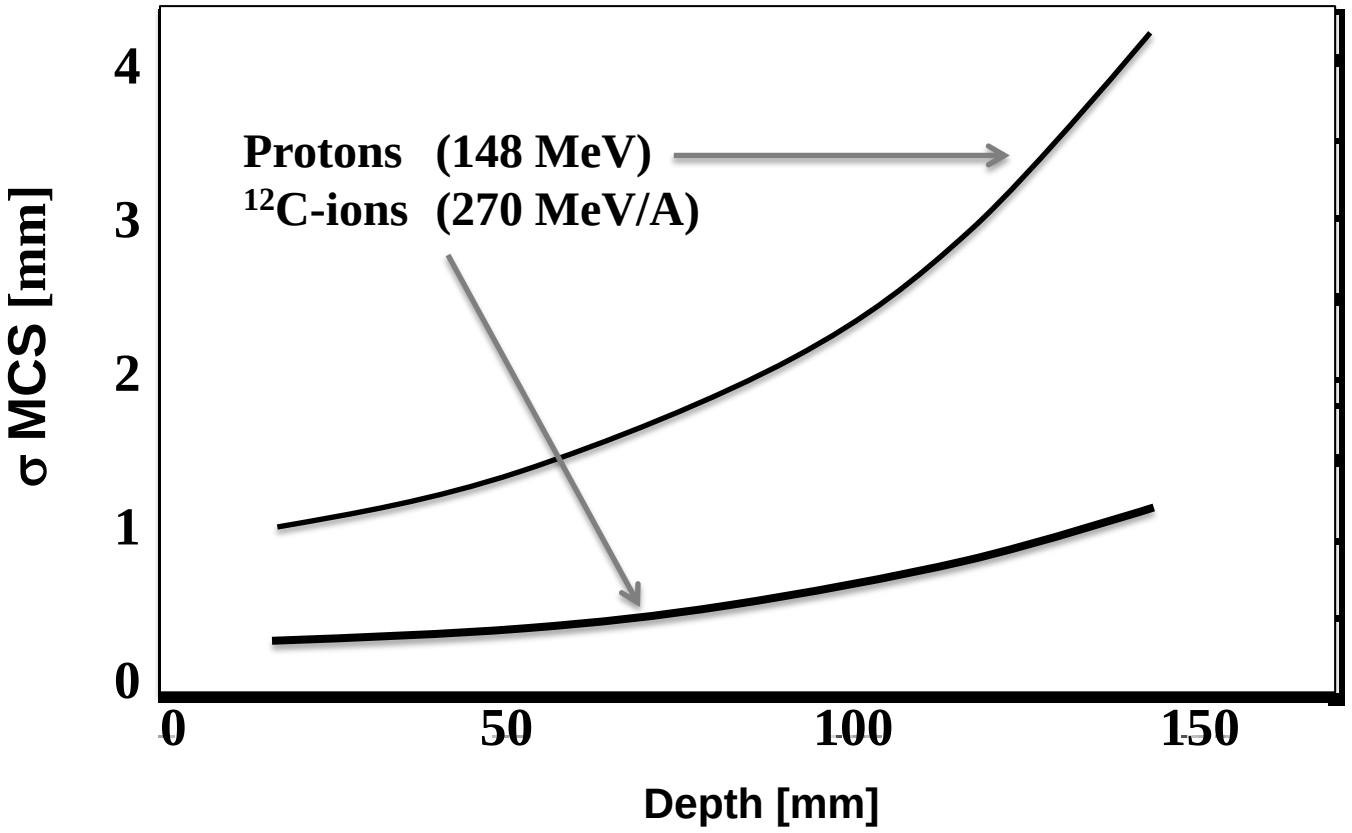
Multiple Coulomb Scattering

- Protons are deflected in the electric field of the nuclei. In general, multiple deflections will occur
- For treatment planning related calculations a purely Gaussian approximation is a good approximation, except at the very end of the range

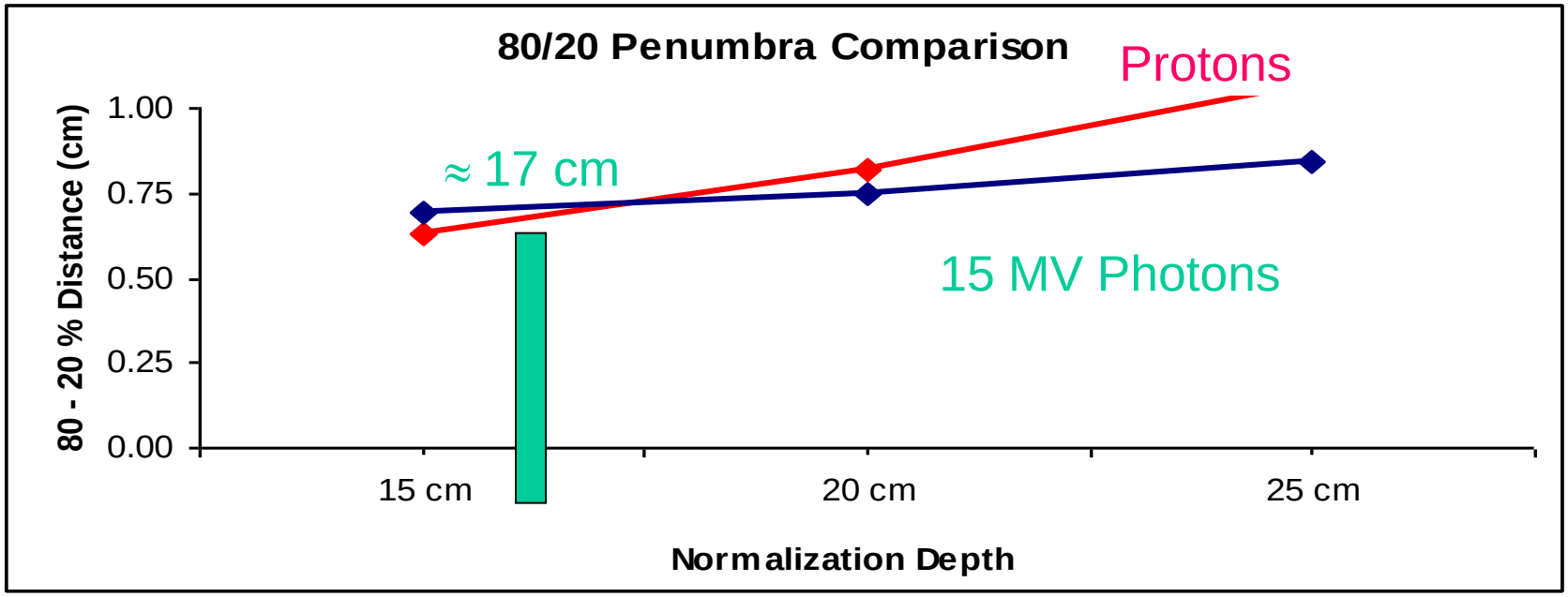
Multiple Coulomb Scattering



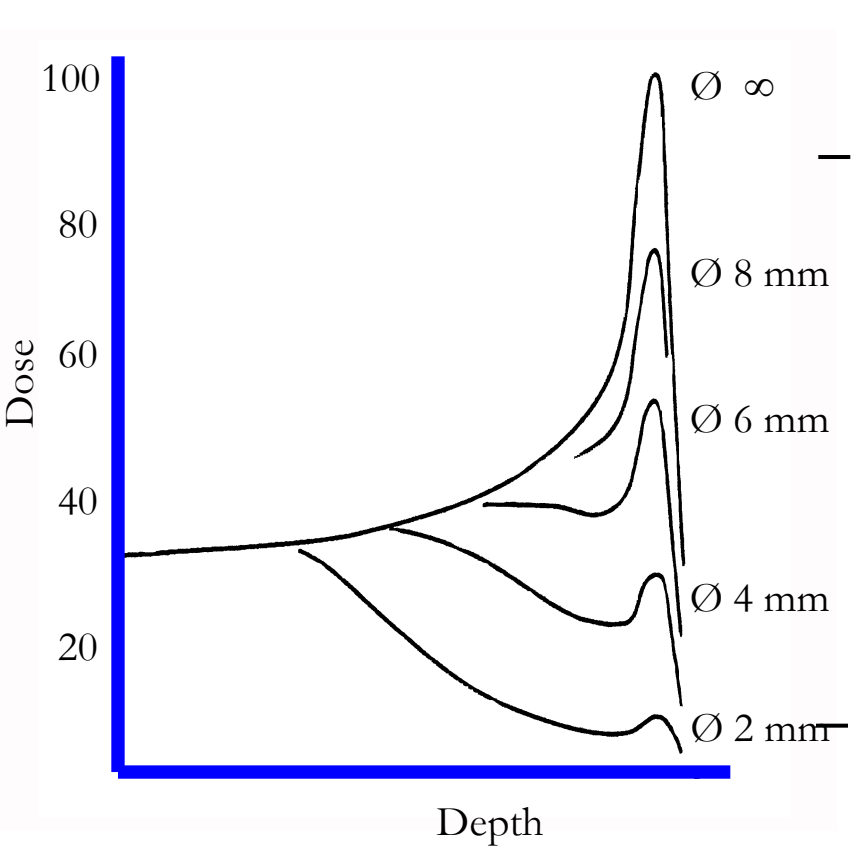
Multiple Coulomb Scattering

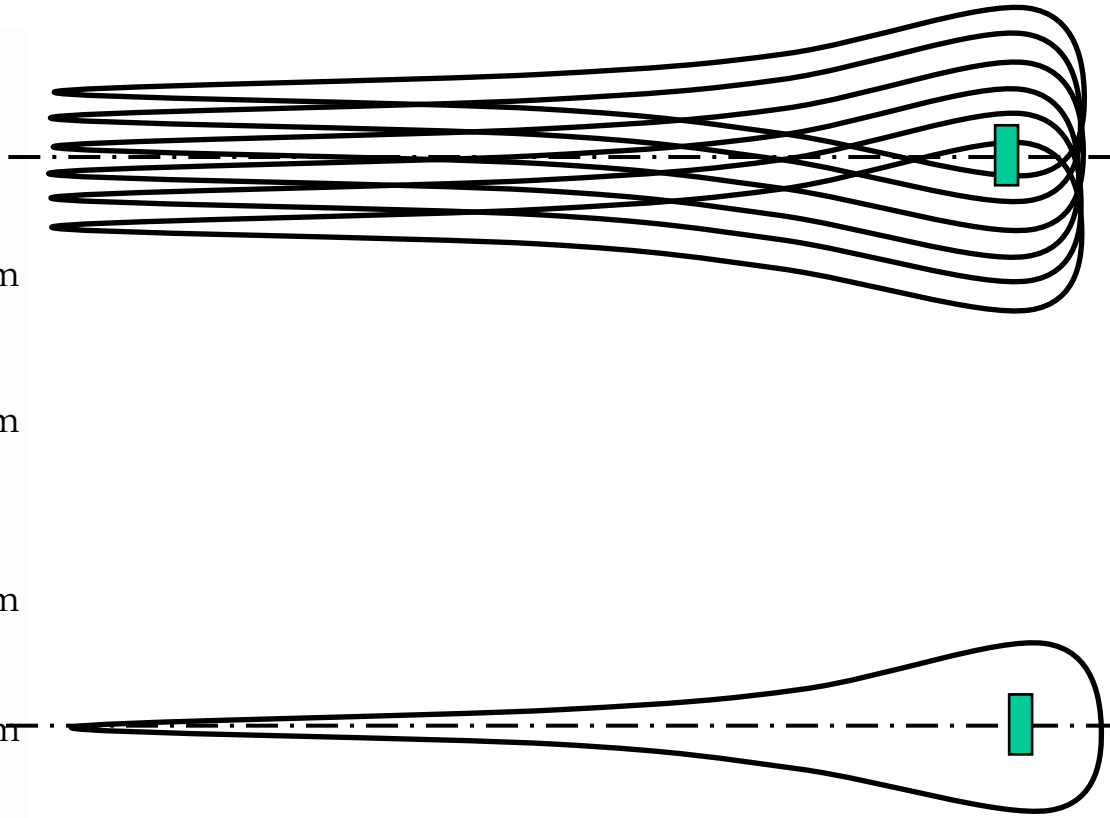


Multiple Coulomb Scattering

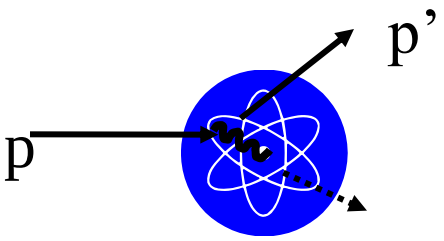


Protons/Ions – Basic Physics

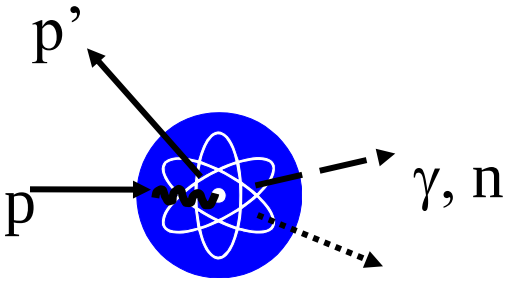




Nuclear interactions of protons



Elastic nuclear collision (large θ)

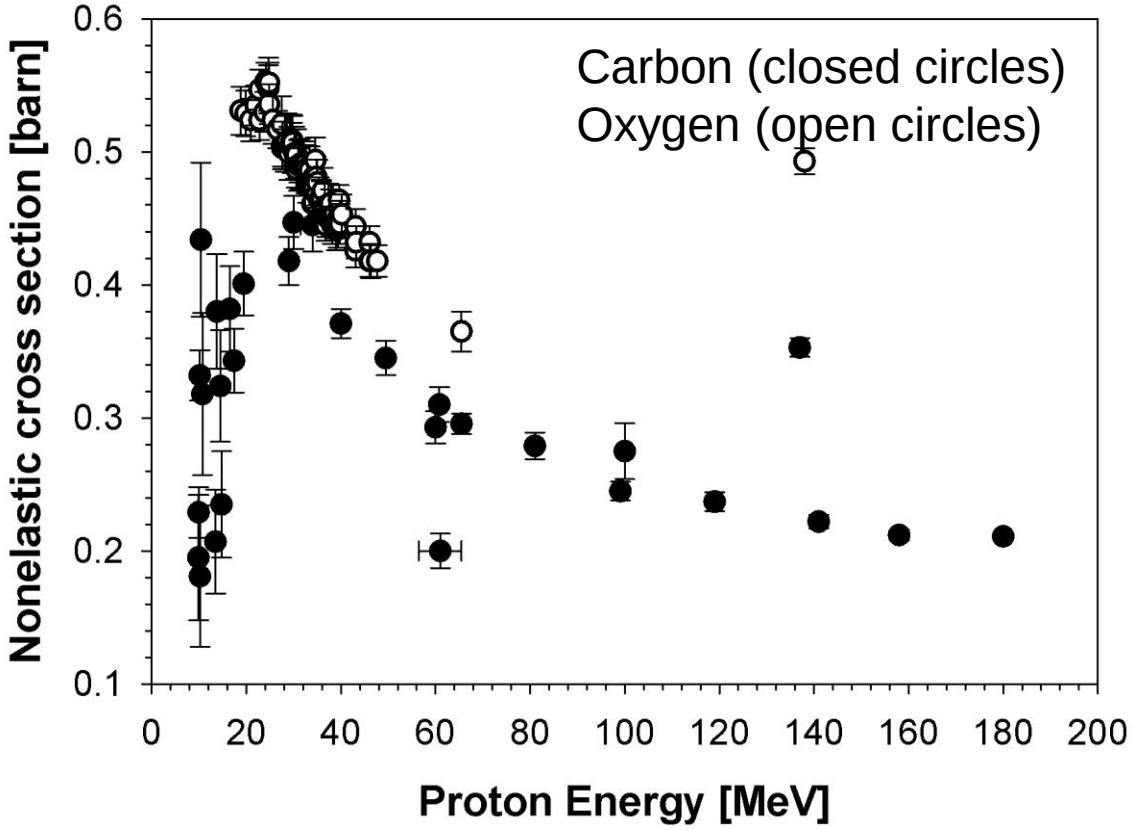


Nuclear interaction

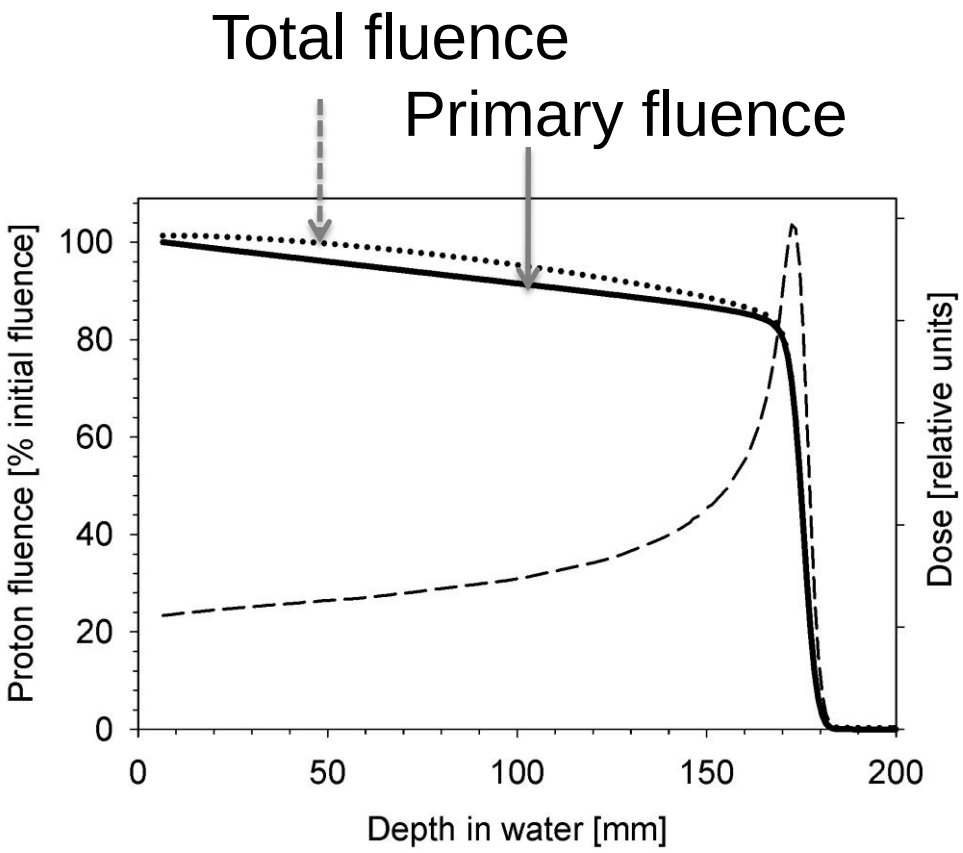
Nuclear interactions of protons

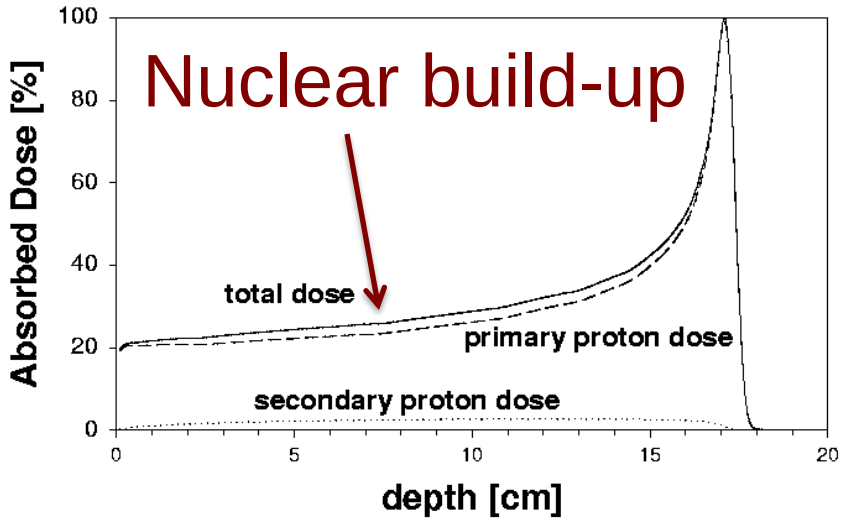
- A certain fraction of protons have nuclear interactions in tissue, mainly with ^{16}O
  (about 1% per cm of all protons)
- Nuclear interactions cause a decrease in primary proton fluence
- Nuclear interactions lead to secondary particles and thus to local and non-local dose deposition (neutrons!)
- The dose from nuclear interactions is negligible in the Bragg peak

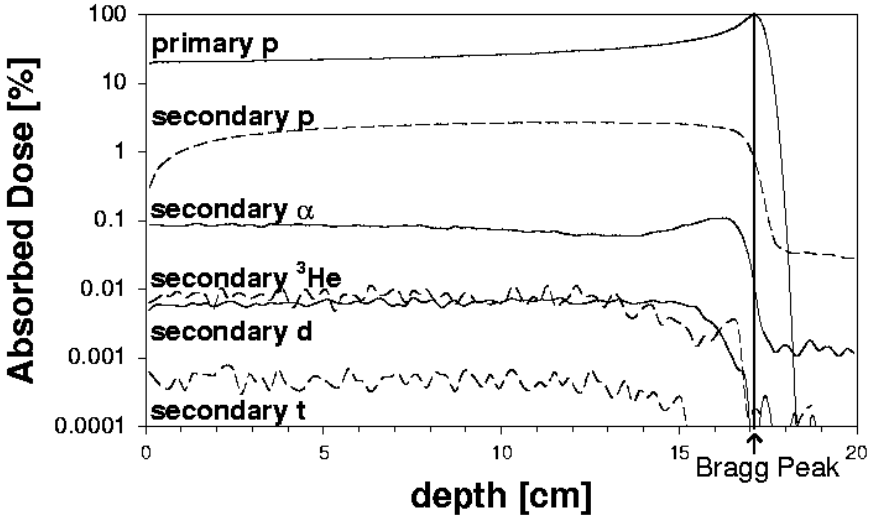
Nuclear interactions of protons



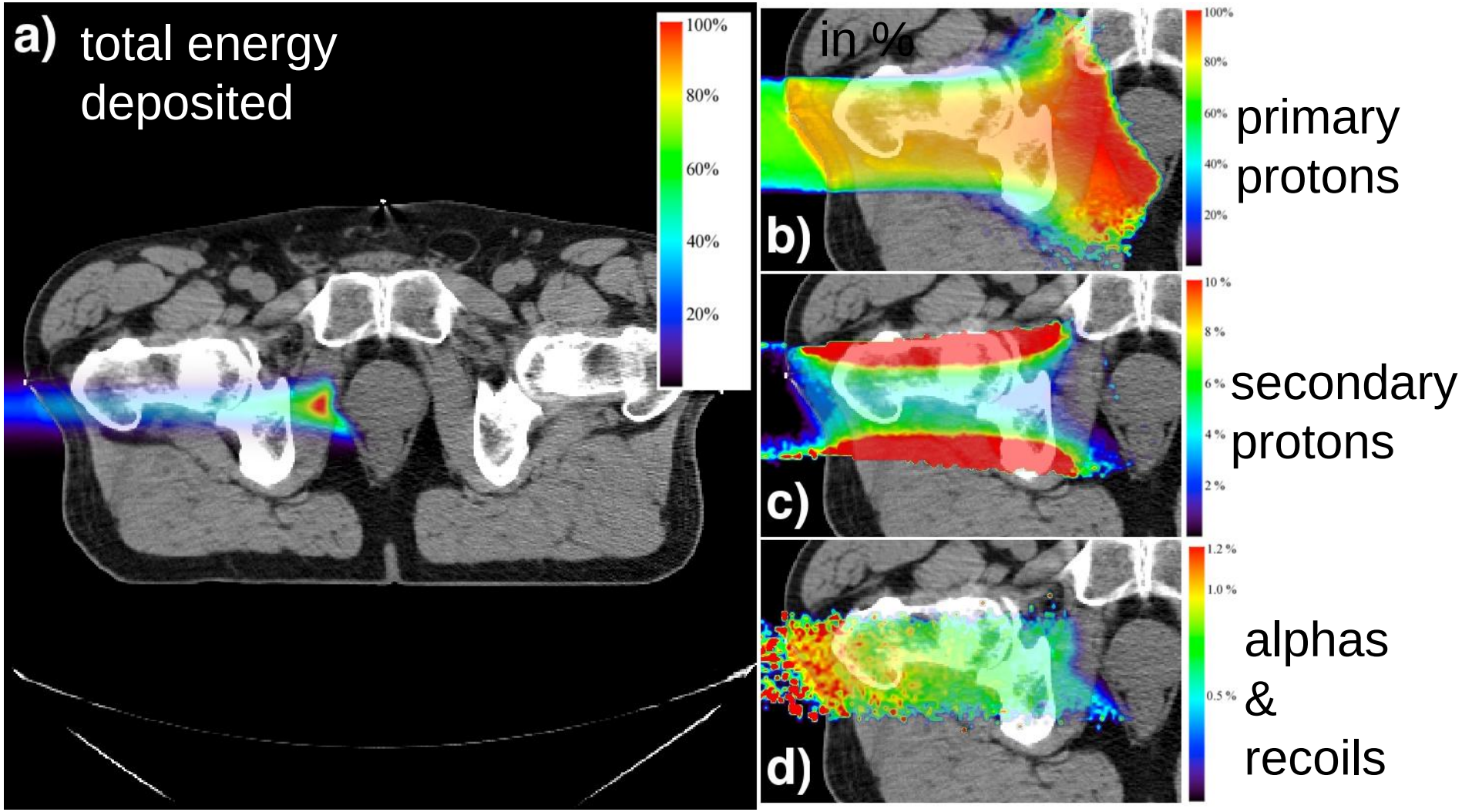
Protons/Ions – Basic Physics



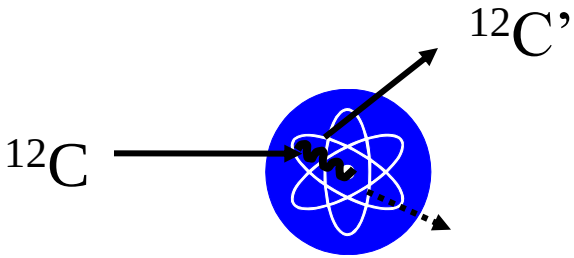




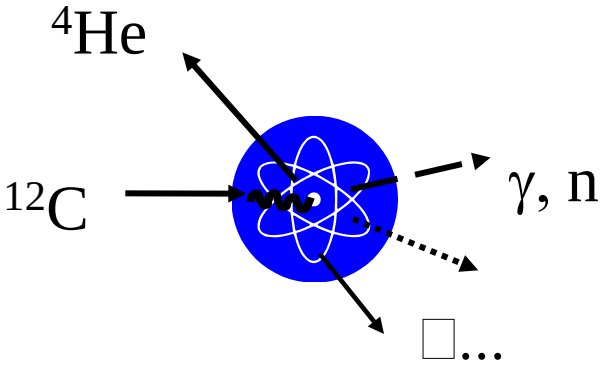
Protons/Ions – Basic Physics



Nuclear interactions of heavy ions

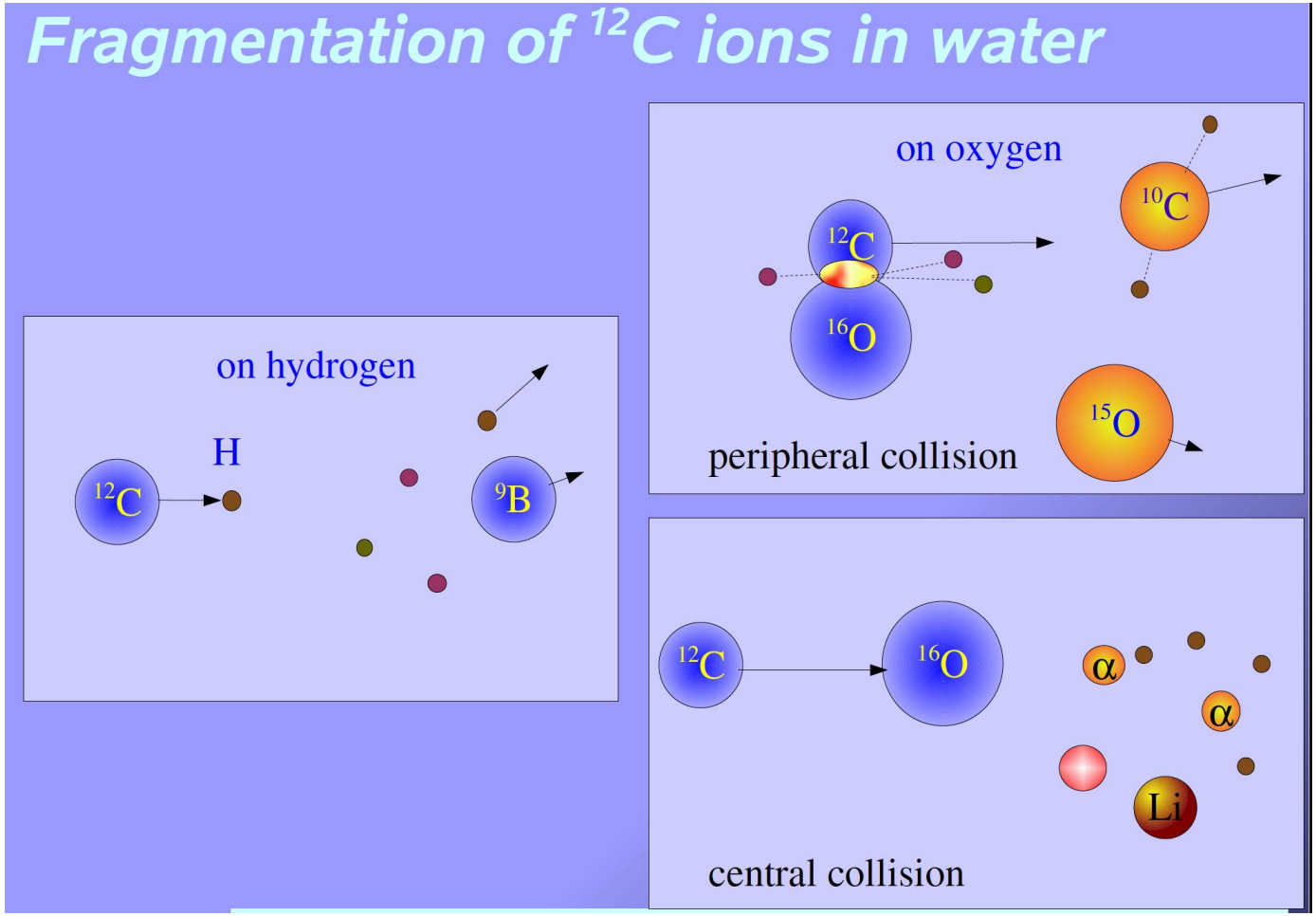


Elastic nuclear collision (large θ)

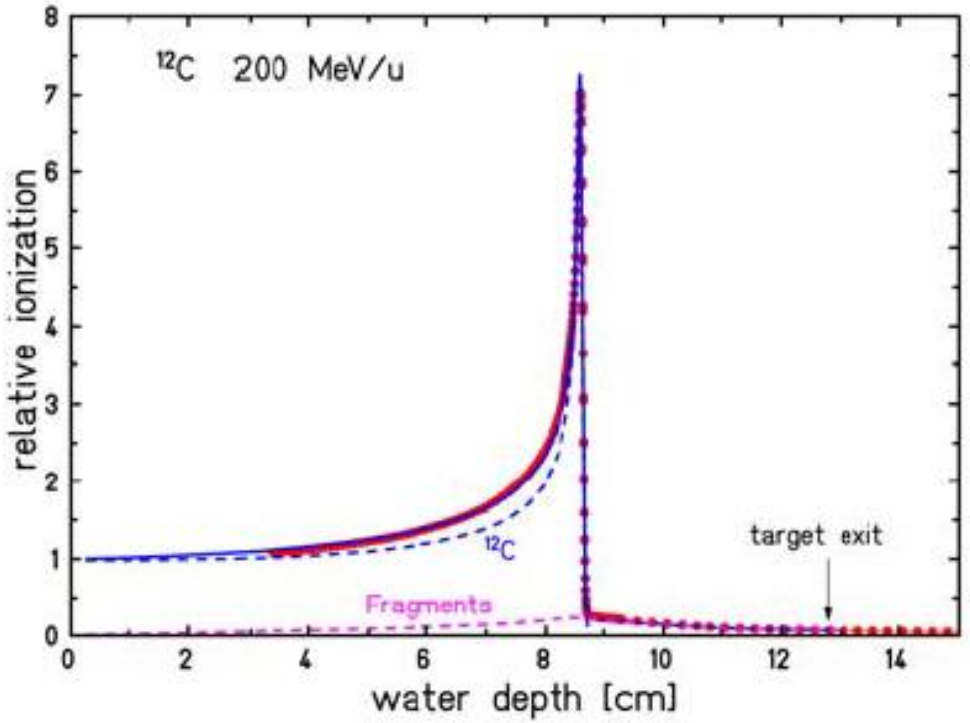


Nuclear interaction (fragmentation)

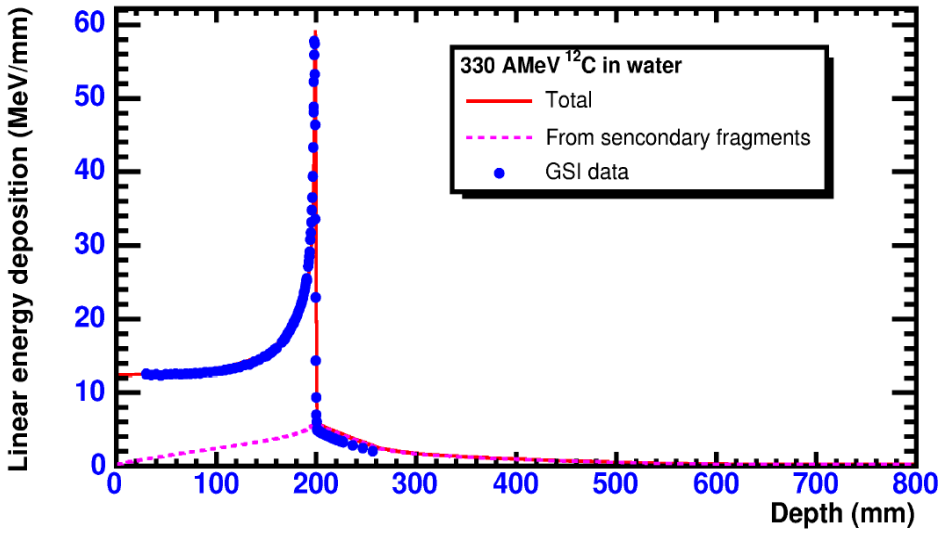
Nuclear interactions of heavy ions

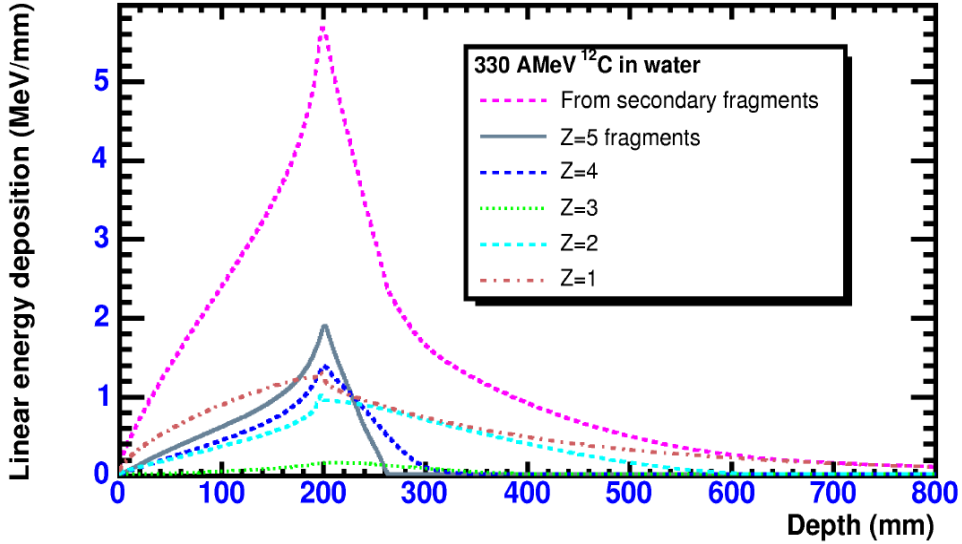


Nuclear interactions of heavy ions

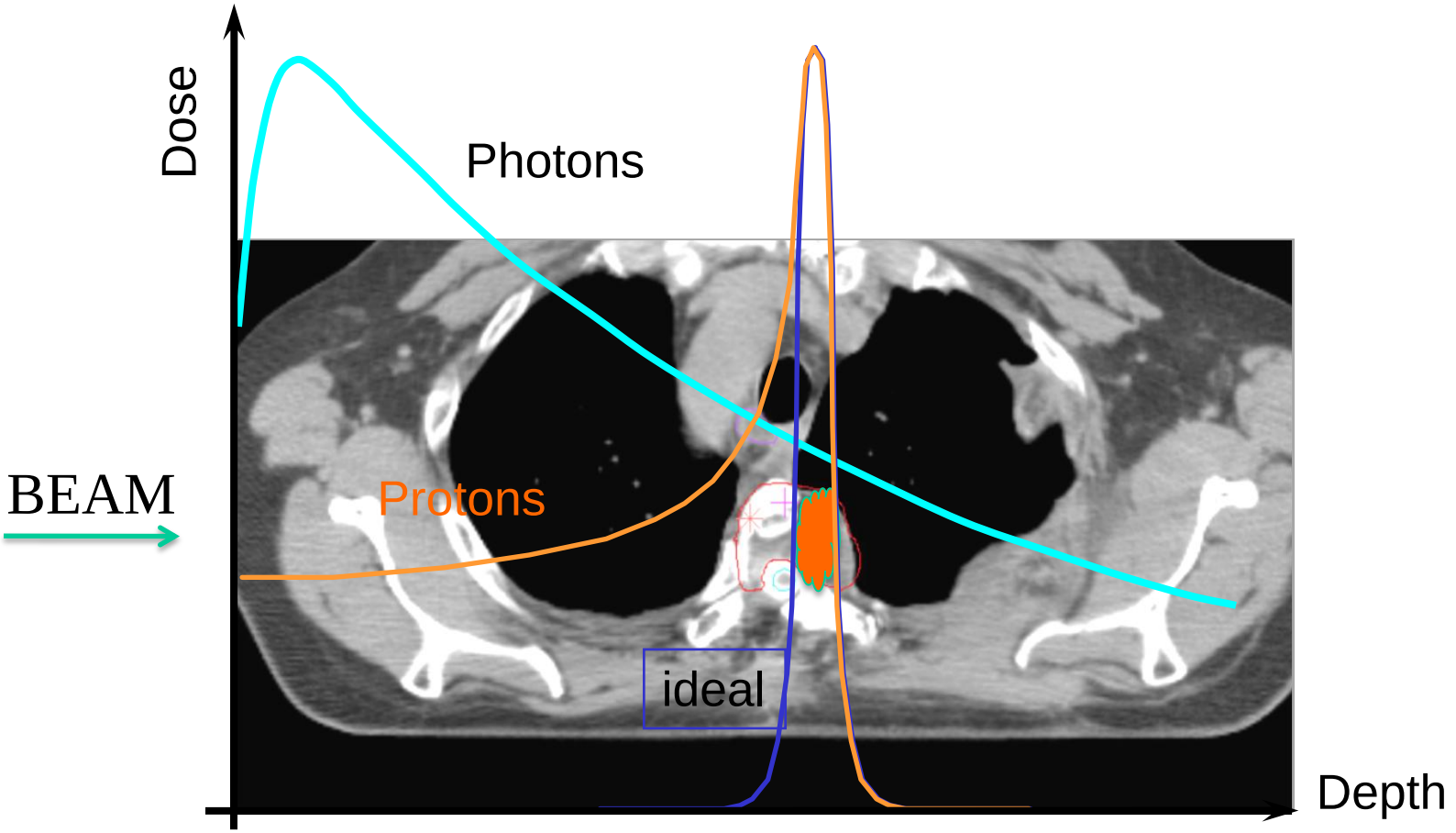


Nuclear interactions of heavy ions

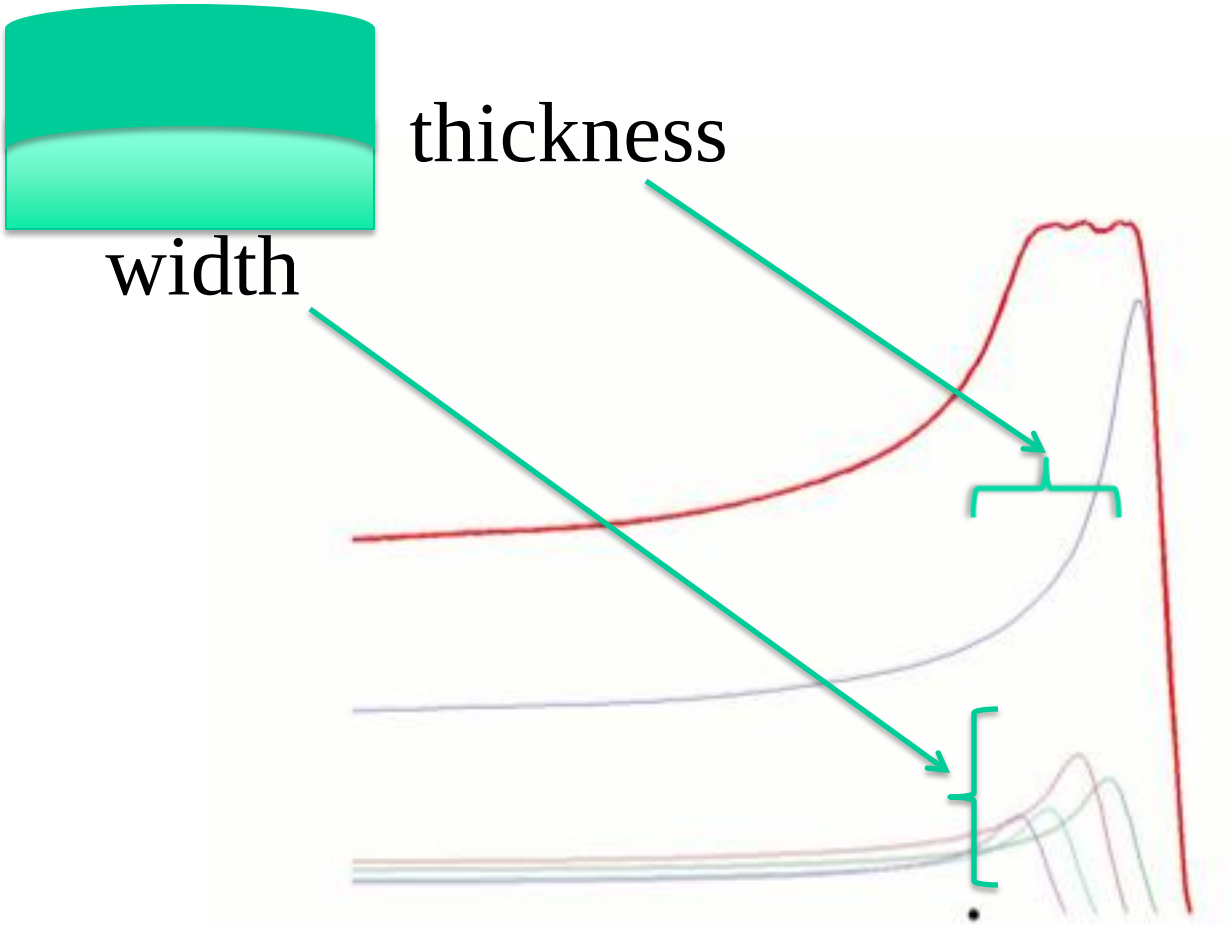




Clinical dose distributions

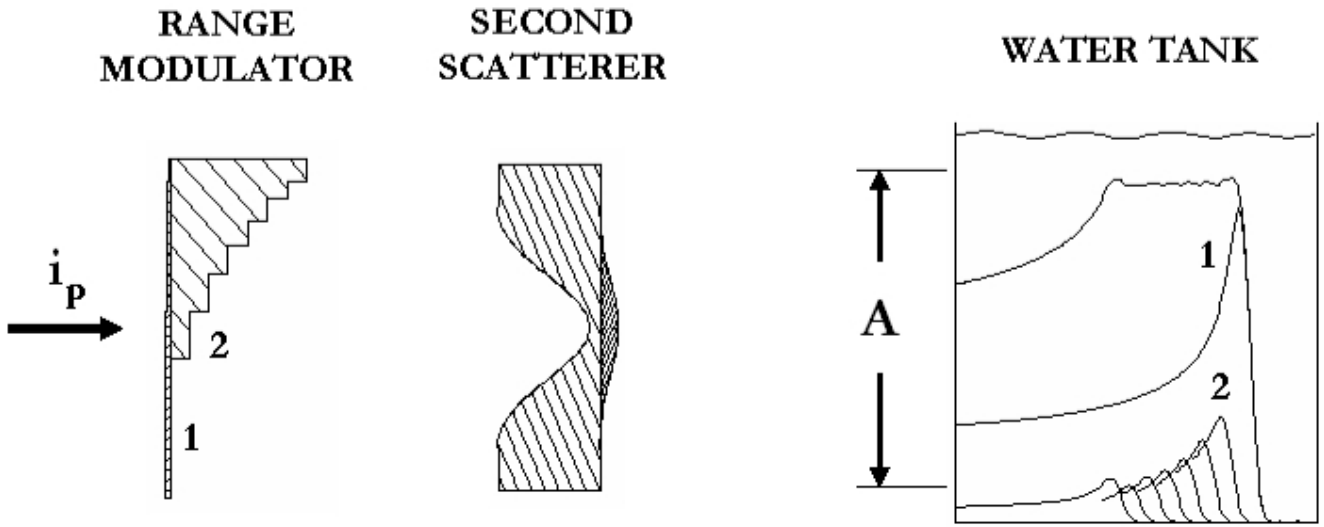


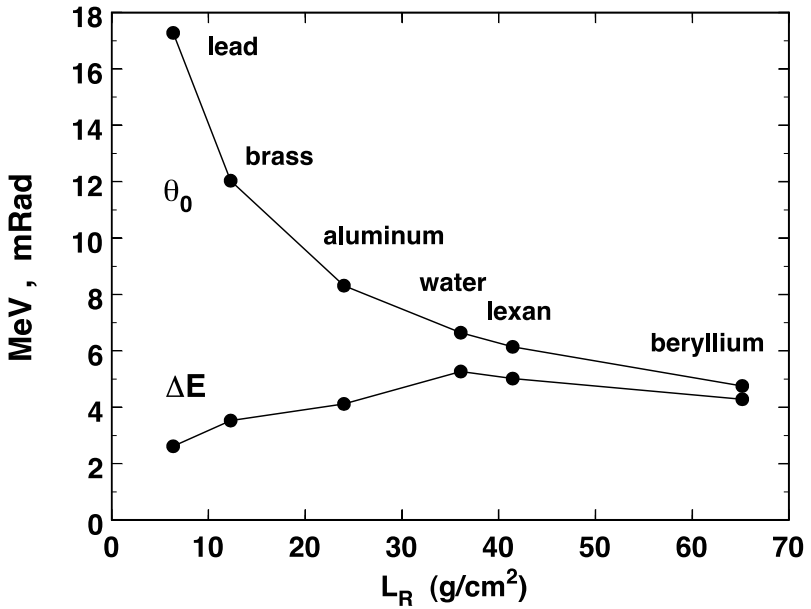
Clinical dose distributions



Spread-out Bragg Peak

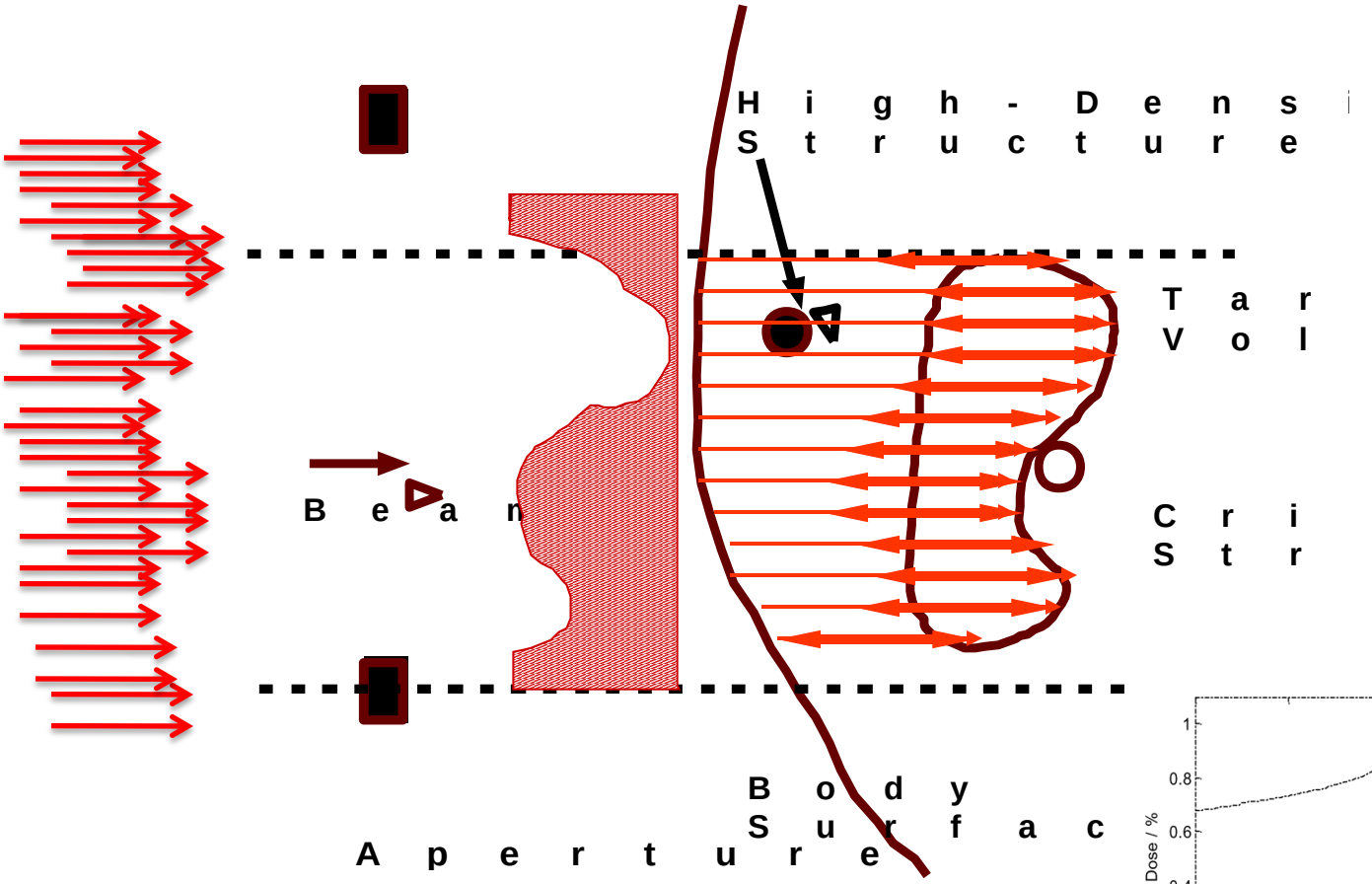
Clinical dose distributions

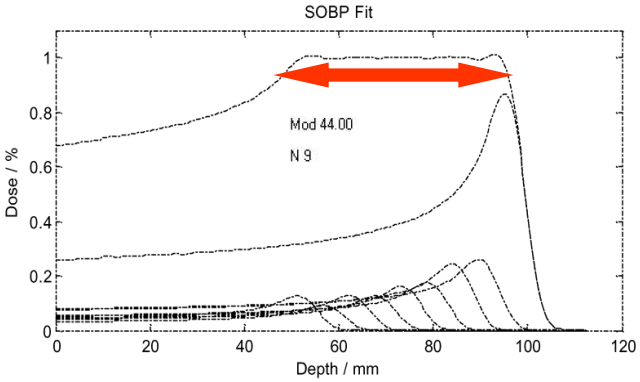




Multiple scattering angle and energy loss for 160 MeV protons traversing 1 g/cm2 of various materials

Clinical dose distributions





Take Home Messages

- Heavy charged particles interact very differently from photons (used in conventional radiation therapy)
- The most important interactions are ionization, Coulomb scattering, and non-elastic nuclear interactions
- Heavy charged particle treatments are associated with the reduction of the total energy deposited in the patient by more than a factor of 2