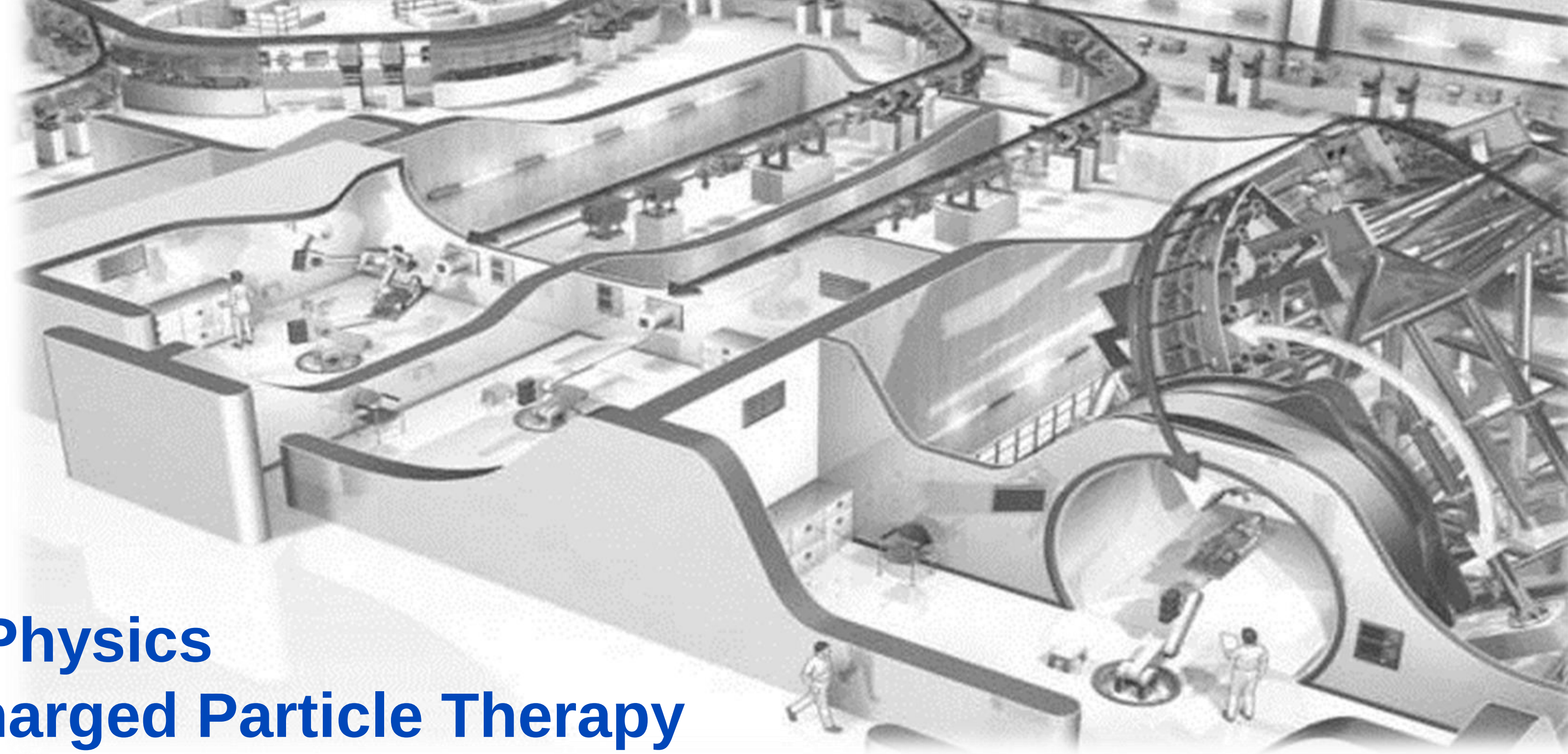
27.04.2020



The Physics of Charged Particle Therapy

Quick Introduction to the Physics of Particle Therapy

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Research for a Life without Cancer
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!! Disclaimer !!

Most (all) slides courtesy of

Dr. Paulo Martins

DKFZ - Division of Biomedical Physics in Radiation Oncology / E041

Literature

- **Radiation Oncology: A Physicist's-Eye View**, Michael Goitein, Springer, Ch. 10, pp. 211-245
- Proton Therapy Physics, Harald Paganetti, Taylor & Francis, Ch. 2-6, pp. 19-190
- The physics of proton therapy, W. D. Newhauser and R. Zhang, *Phys. Med. Biol.* **60** (2015) R155-R209
- Nuclear physics in particle therapy: a review, M. Durante and H. Paganetti, *Rep. Prog. Phys.* **79** (2016) 096702 (59pp)

Additional Literature

- Schardt, Dieter, Thilo Elsässer, and Daniela Schulz-Ertner. "Heavy-ion tumor therapy: Physical and radiobiological benefits." Reviews of modern physics 82.1 (2010): 383.
- Wilson, Robert R. "Radiological use of fast protons." Radiology 47.5 (1946): 487-491.

The Ideal Irradiation Type

In cancer, the ideal radiation delivers:

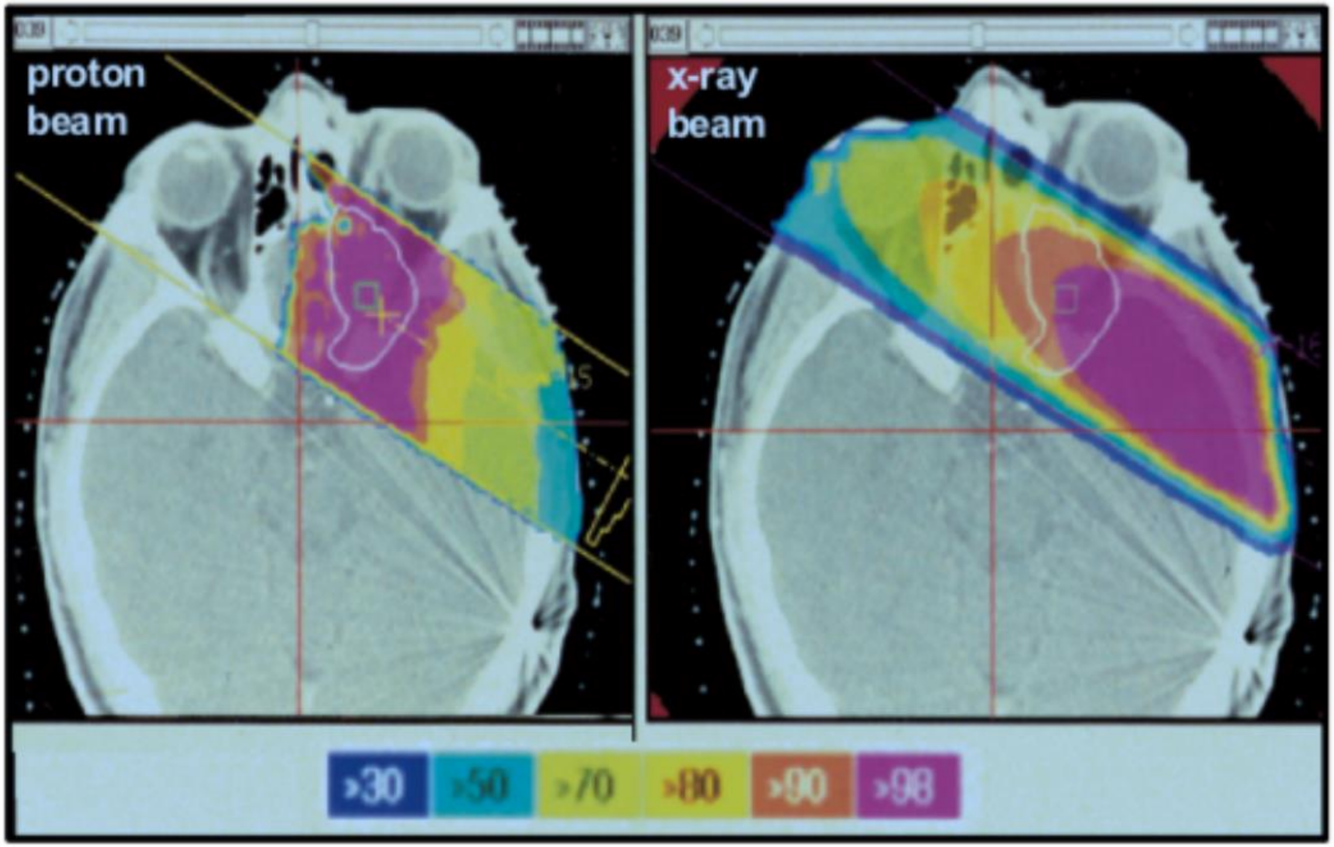
In theory:

- defined dose distribution within the target volume (generally a uniform);
- None outside it.

In practice:

- most of the dose within the target volume
- relatively little outside it

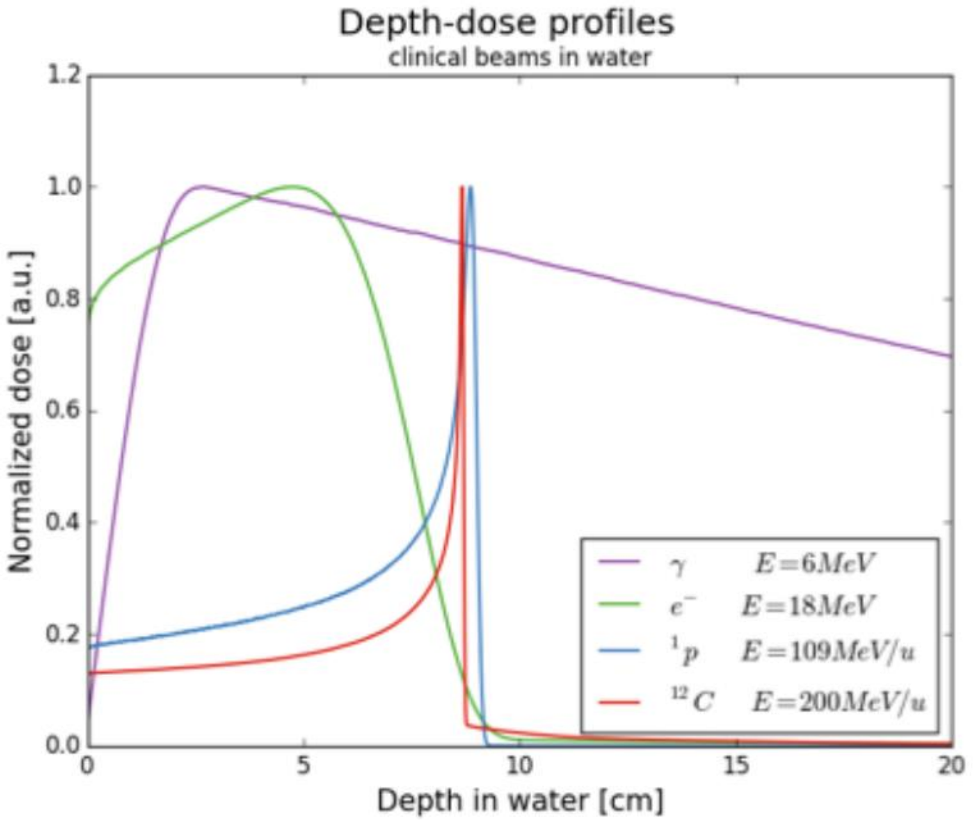
A Quick Comparison

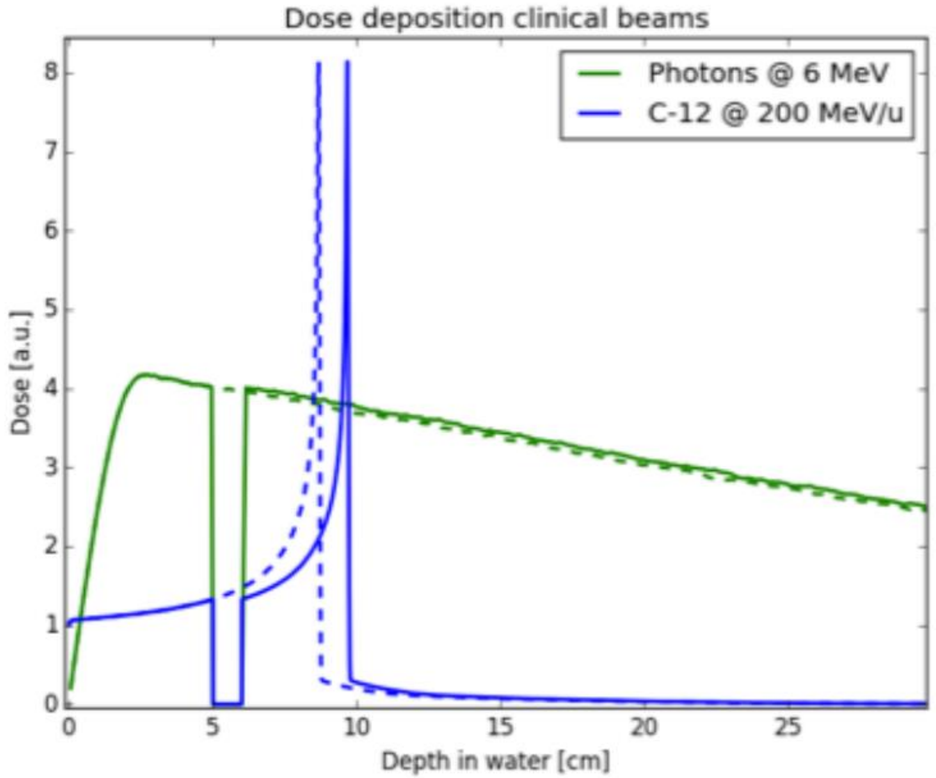


Proton and a photon posterior-oblique beam

M. Goitein 2008

Dose Deposition





Physics of Particles

Three main phenomena:

- Coulomb interactions with atomic electrons
- Coulomb interactions with atomic nuclei
- Nuclear interactions with atomic nuclei

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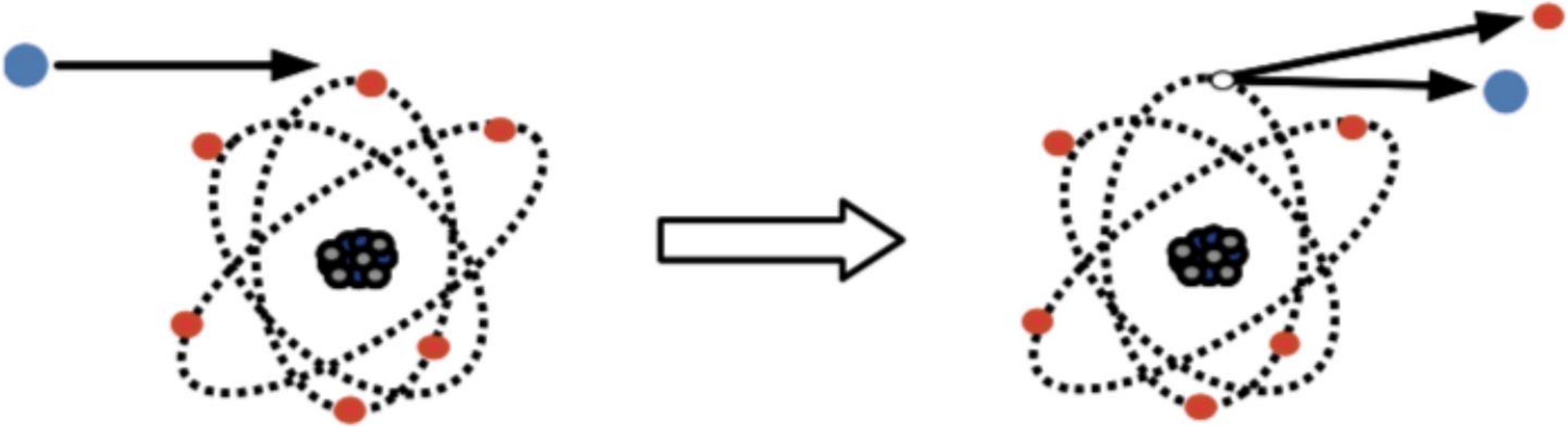
Coulomb Interaction with Electrons



Coulomb interaction of a proton with an atomic electron

M. Goitein 2008

The Bragg-Peak

Energy loss due to Coulomb interaction with atomic electrons

Slow energy loss, mainly transferred to atomic electrons, give rise to the Bragg peak

In a stopping medium, the proton's linear rate of energy loss (linear energy transfer – LET or stopping power) is given by the Bethe-Block formula:

$$\frac{dE}{dx} \propto \frac{1}{v^2}\left(\frac{Z}{A}\right)z^2$$

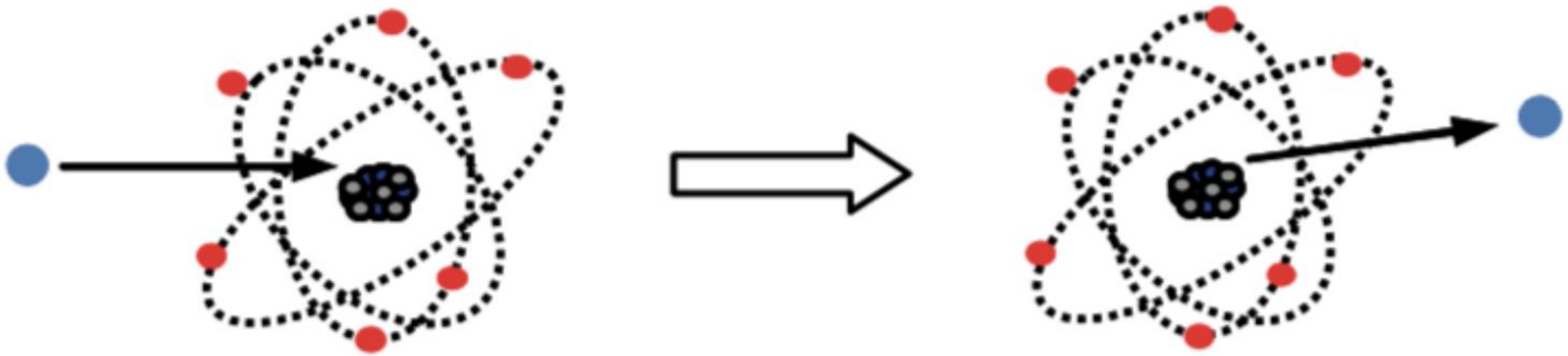
Local energy deposition increases as protons slow down

Physics of Particles

Three main phenomena:

- Coulomb interactions with atomic electrons
- Coulomb interactions with atomic nuclei
- Nuclear interactions with atomic nuclei

Coulomb Interaction with Nuclei



Coulomb scattering of a proton by an atomic nucleus

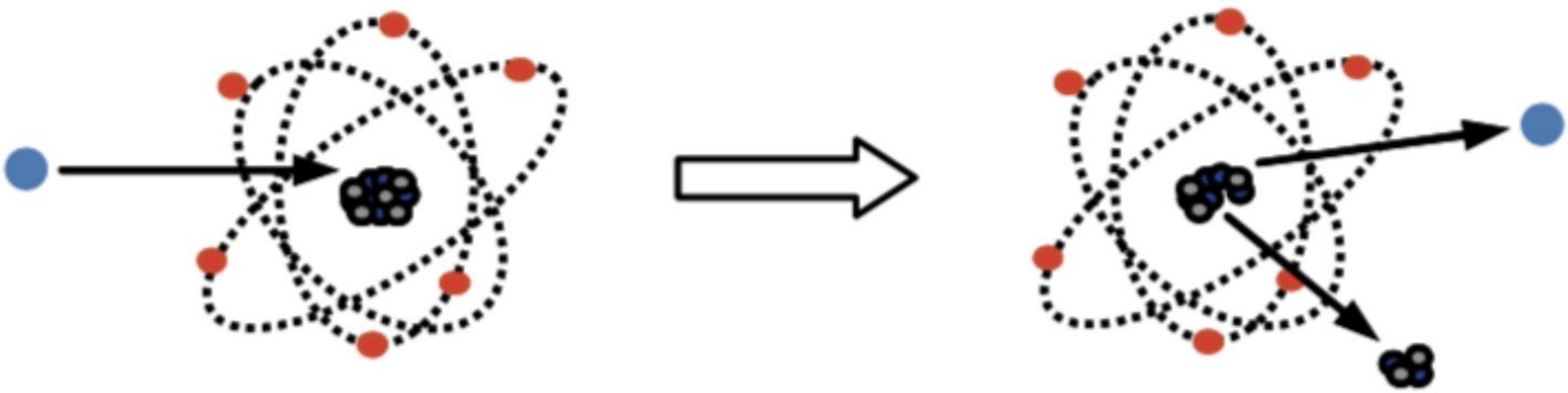
M. Goitein 2008

Physics of Particles

Three main phenomena:

- Coulomb interactions with atomic electrons
- Coulomb interactions with atomic nuclei
- Nuclear interactions with atomic nuclei

Nuclear Interactions



Non-elastic nuclear collision of a proton with an atomic nuclei

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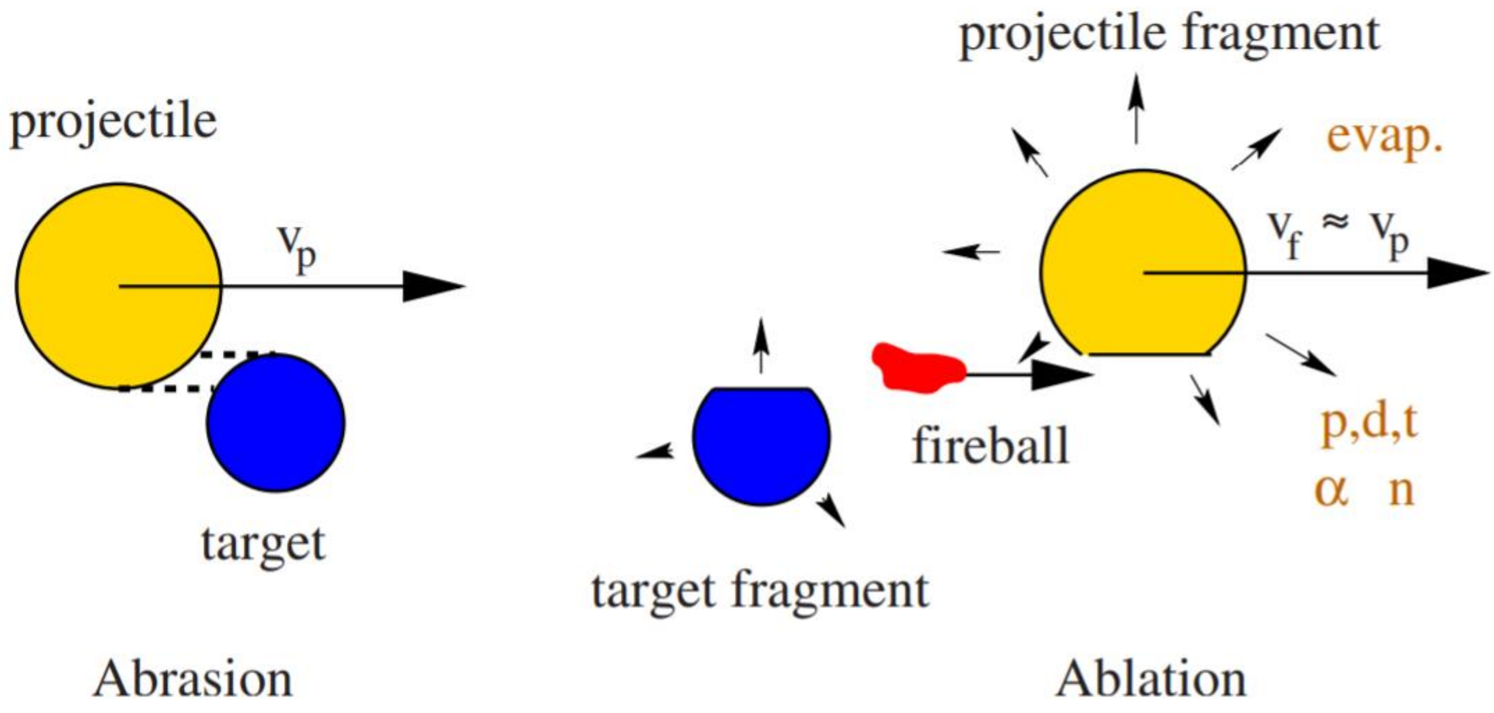
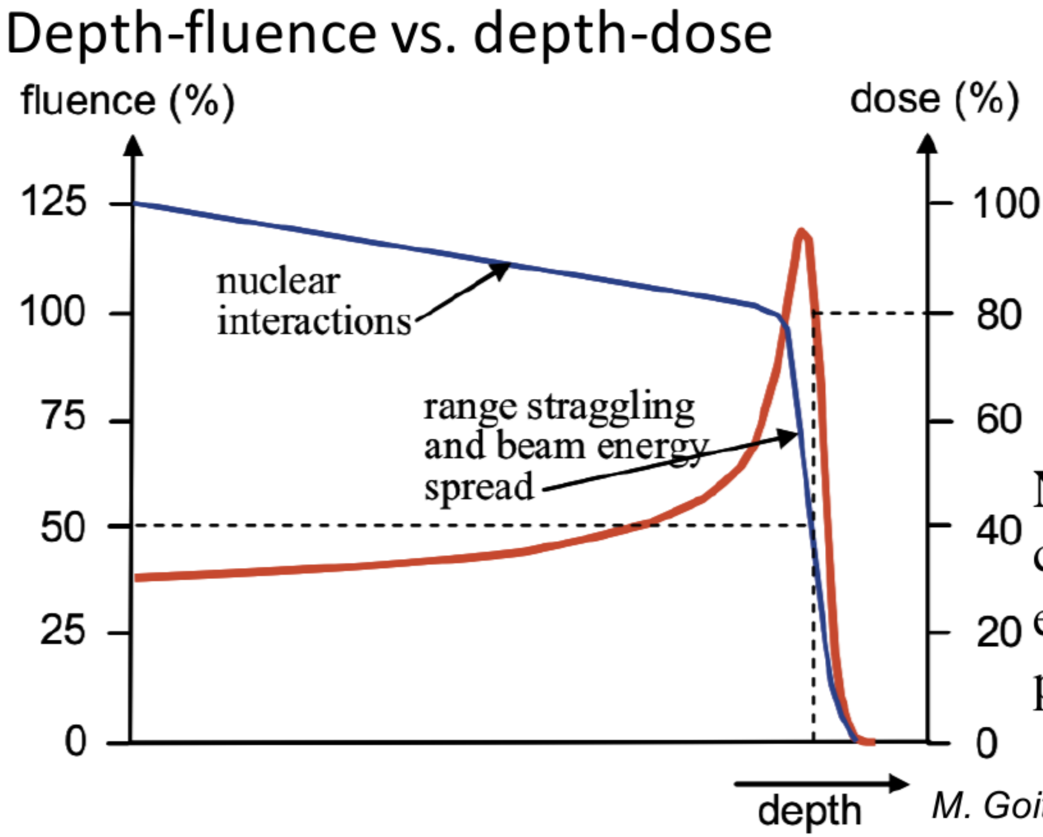
Nuclear Interactions of Heavy Projectiles

Heavy Particles e.g. Carbon, Oxygen, Neon ions ...



Taken from Schardt 2010 et al.

Nuclear Interactions



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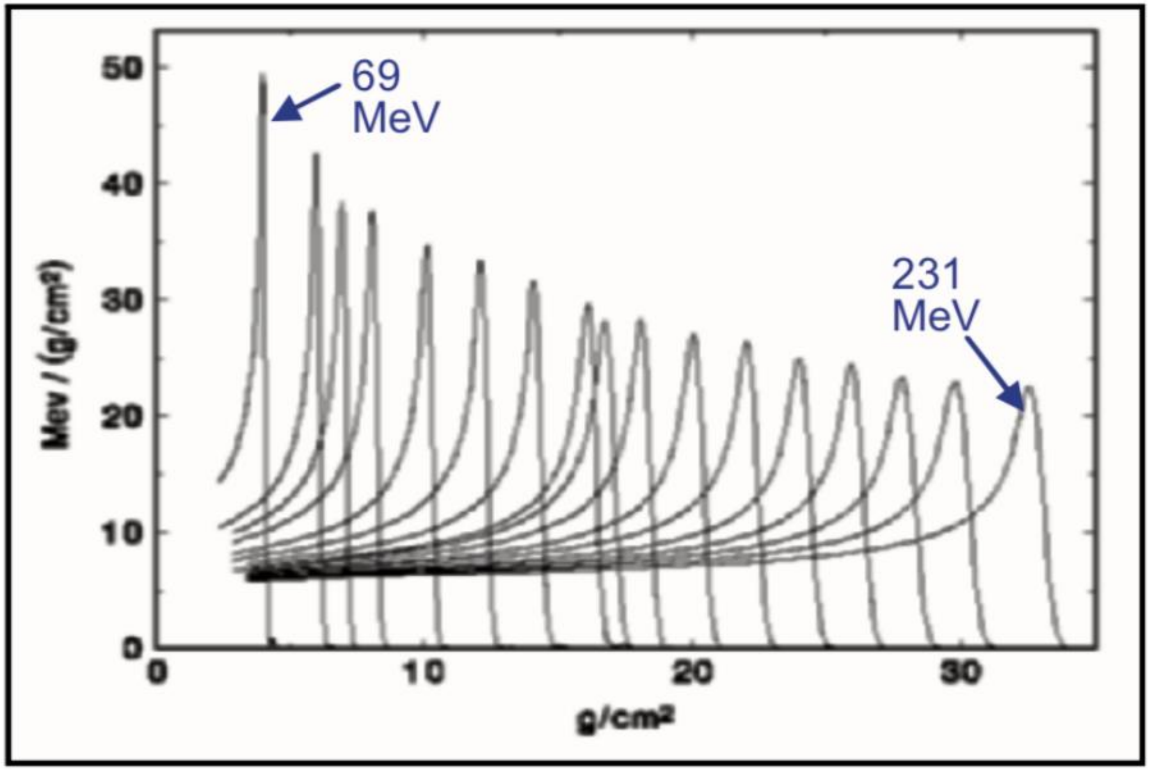
80 % dose BP falling edge
same depth
50 % fluence FD falling edge

Near-flat plateau – fortuitous cancellation between increasing energy deposition and decreasing primary protons (nucl. interactions)

Range Straggling

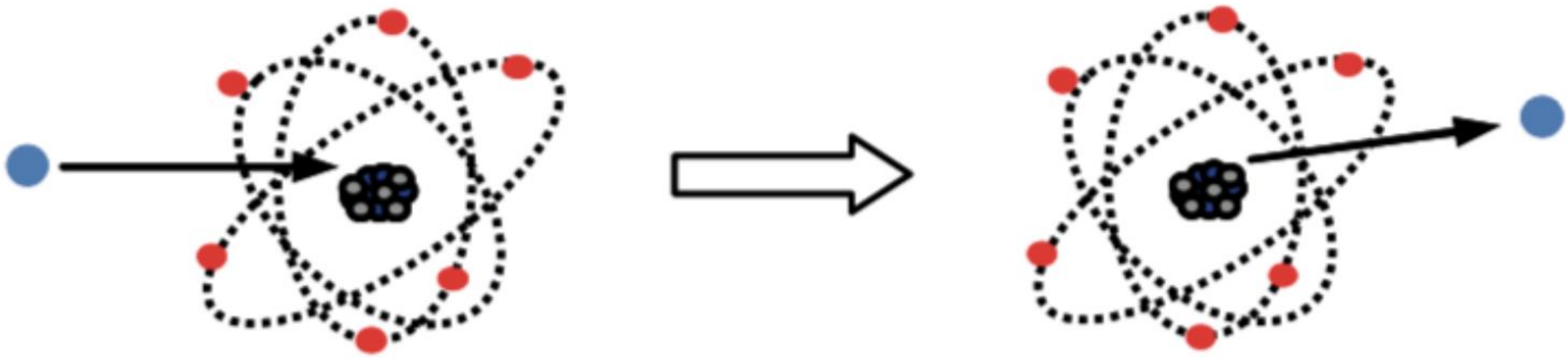


Lower energies
-> narrower BPs
-> higher peak-to-plateau ratio

Range straggling and energy spread spread out the BP (1.5% range)

B. Gottschalk 2004

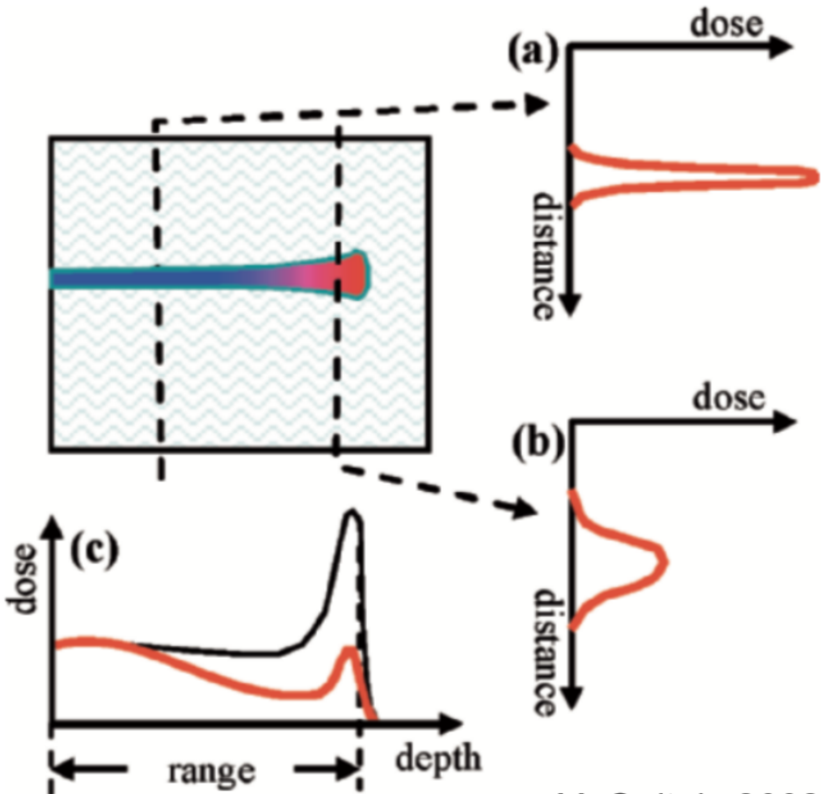
Coulomb Interaction with Nuclei



Coulomb scattering of a proton by an atomic nucleus

M. Goitein 2008

Lateral Beam Shape



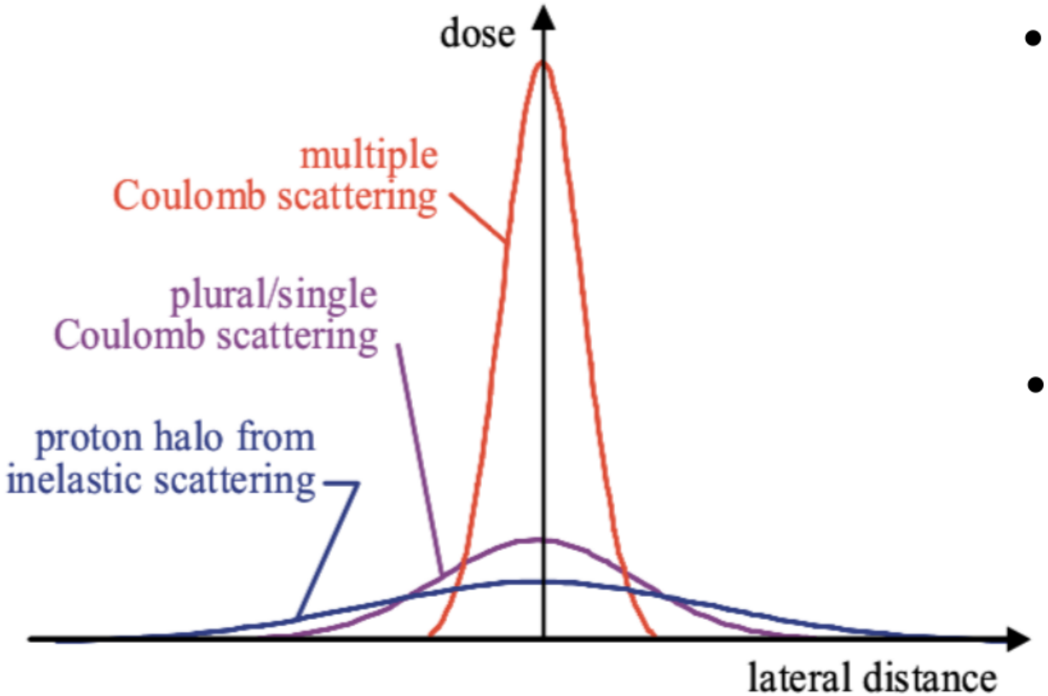
M. Goitein 2008

Lateral dose distribution are broader but shallower at larger depths (lower amplitude but great lateral extent)

Protons going deeper are more scattered and spread out and the energy at the BP is smeared out laterally

-> not well suited for very small (mm) deep seated tumors (many cm)

Lateral Beam Shape



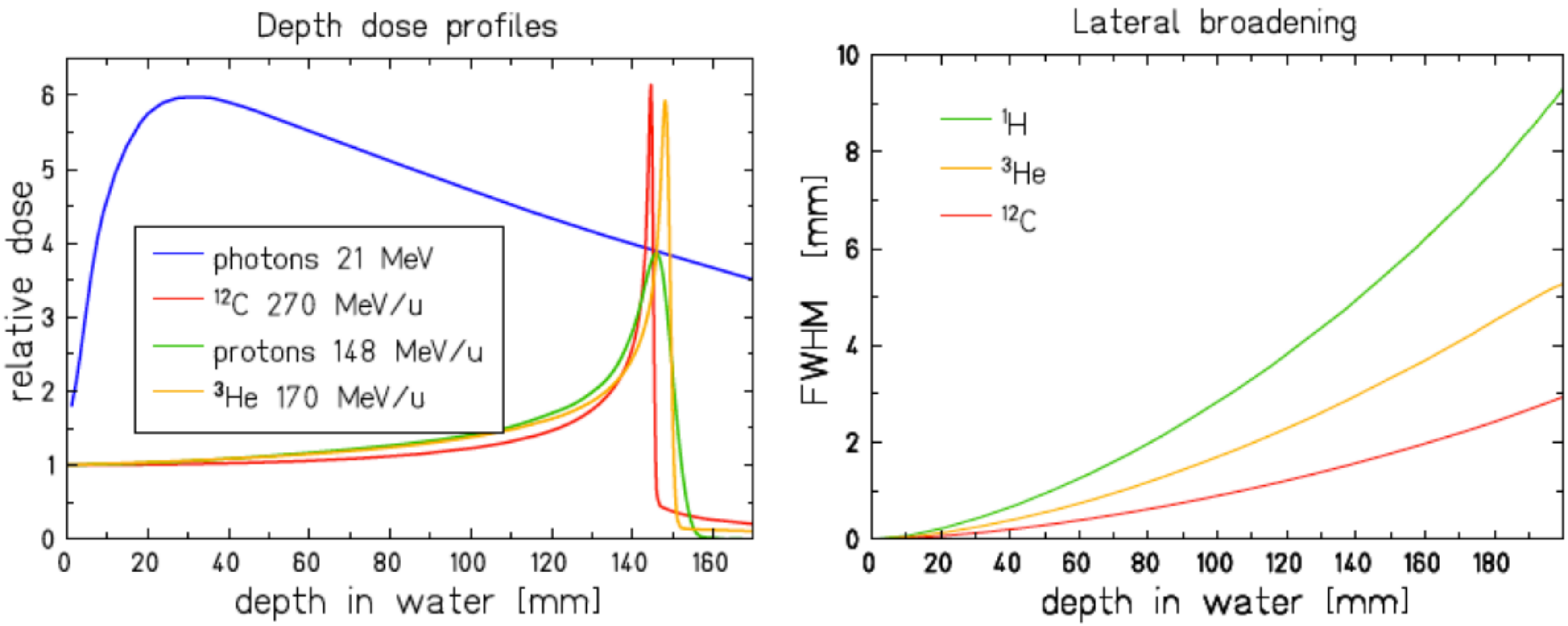
- Multiple Coulomb scattering:
  - near-Gaussian core
  - long tail
- Nuclear interactions:
  - protons
  - neutrons

M. Goitein 2008

Three charged particle components of the lateral profile of a pencil beam

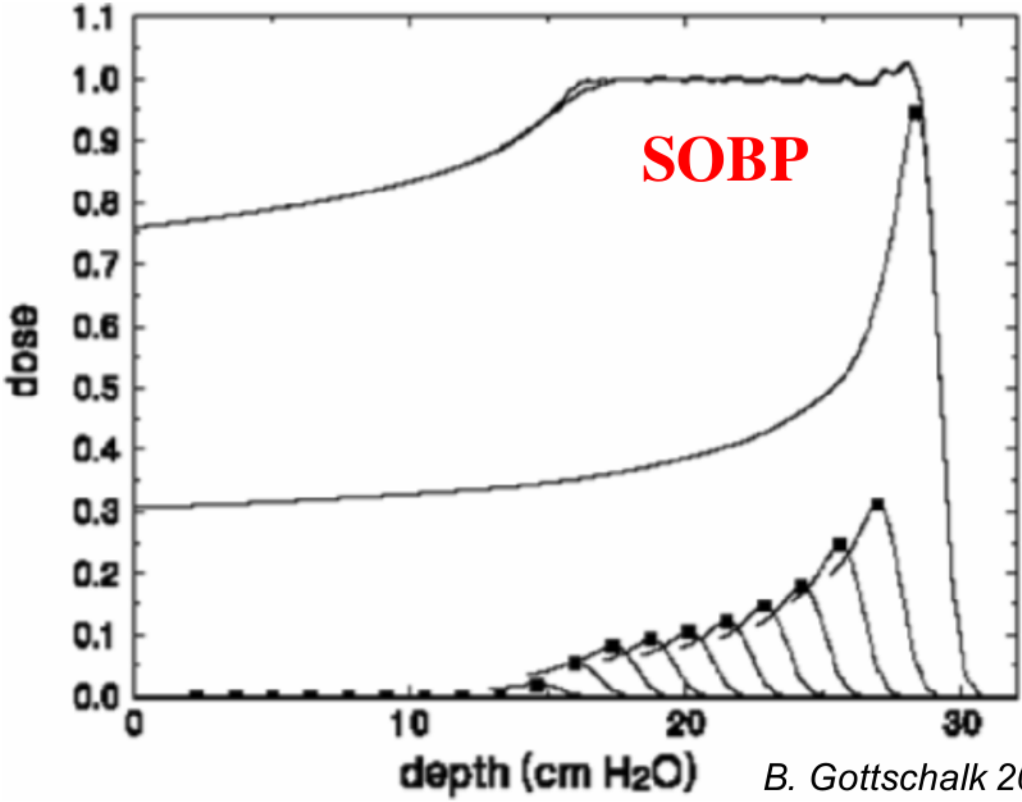
Lateral Beam Shape

Lateral dose distribution of charged particles



Krämer et al., (2016) Med. Phys. 43 (4), 1995

The Spread-Out Bragg Peak (SOBP)



B. Gottschalk 2004

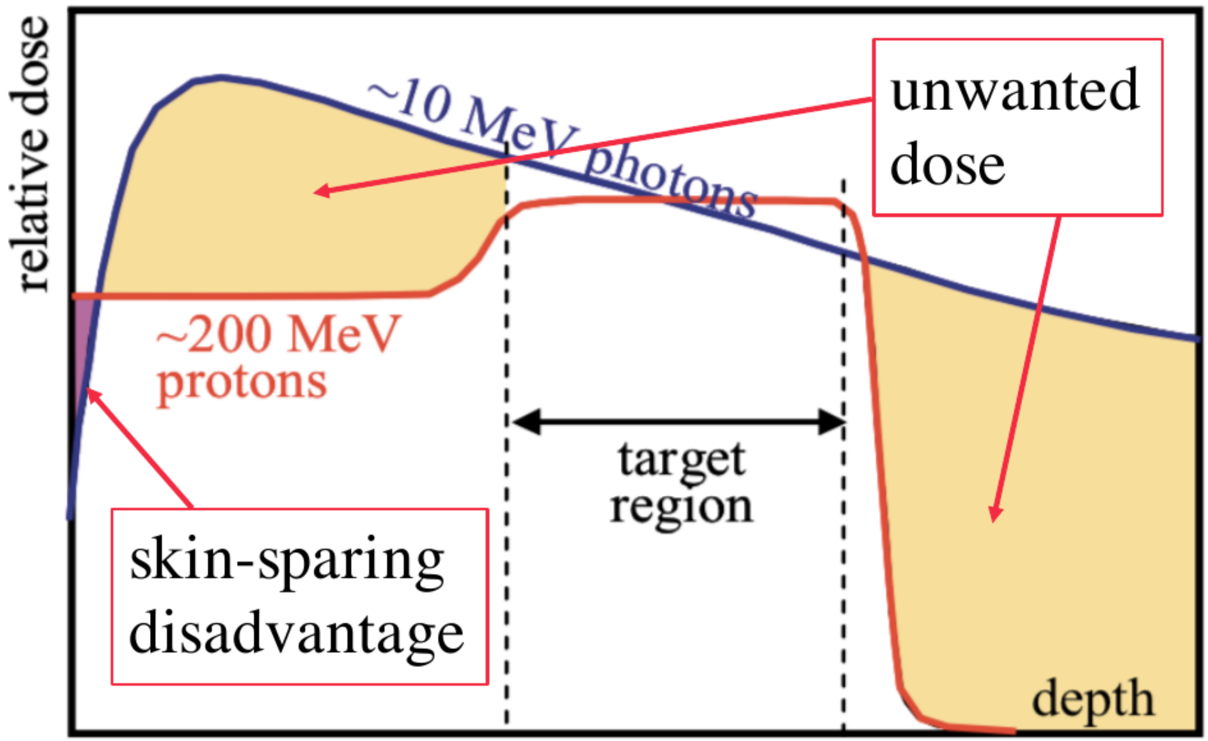
Tumors may extend more than 10 cm

This extension is achieved by delivering many BPs with different ranges/energies and weights

More proximal –> less weight

Near-constant high dose at distal region -> **spread-out Bragg peak (SOBP)**

The Spread-Out Bragg Peak (SOBP)

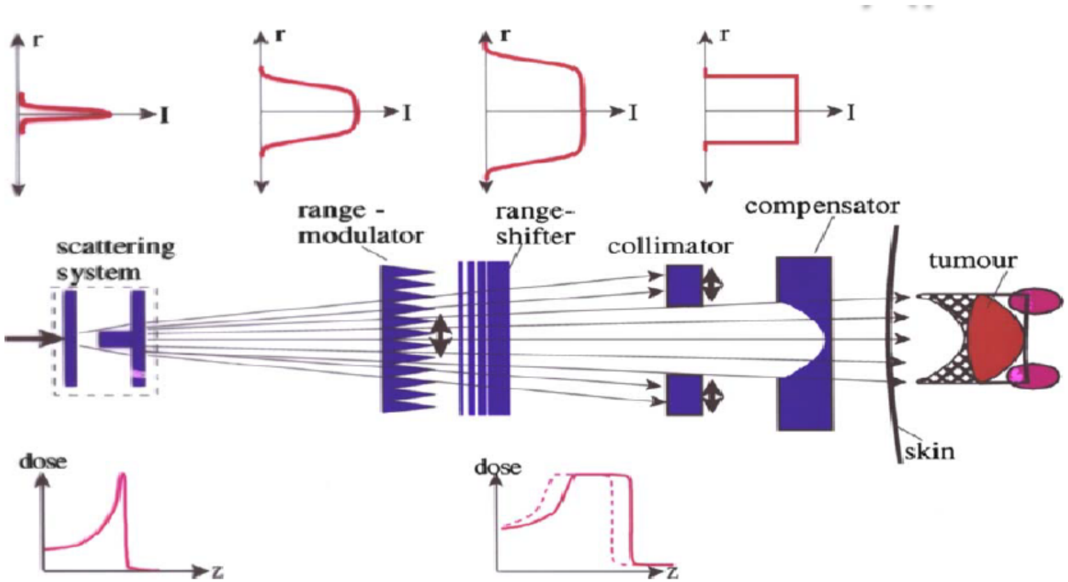


M. Goitein 2008

Proton SOBP dose distribution much superior to the one from a photon beam (LINAC)

Entrance dose depends SOBP extent -> up to 80%

Passive Beam Delivery



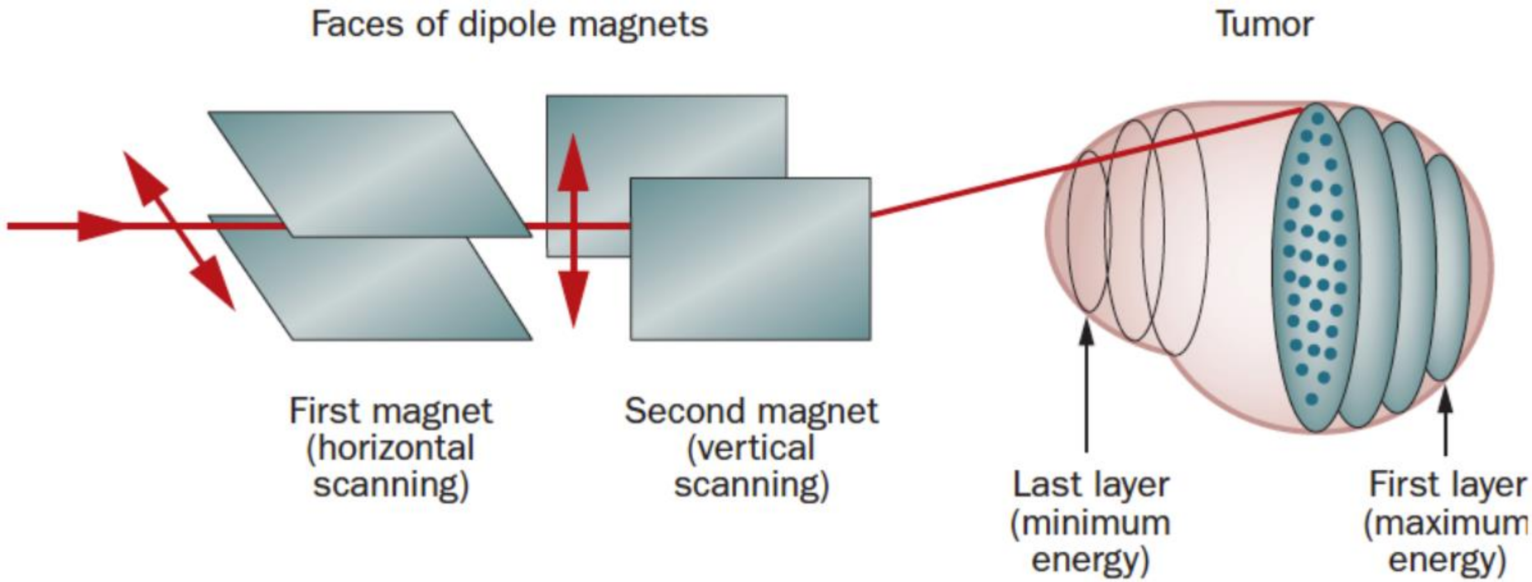
Single-scatter:
Excellent penumbral quality
Not too large fields
Double-scatter:
Larger penumbra
Must be very well centered
More efficient (transmits up to 45% of the beam)
Reduction of secondary dose

- Double-scattering system generates a flat transversal profile (spreading laterally)
- Mono-energetic Bragg peak is spread out by a range modulator (spreading in depth)
- SOBP can be shifted in depth by absorber plates ("range shifter")
- The collimator cuts out the field area defined by the largest target contour
- The range compensator adjusts the distal depth pattern

Schardt & Elsässer, (2010) Rev. Mod. Phys. 82, 383

Active Beam Delivery

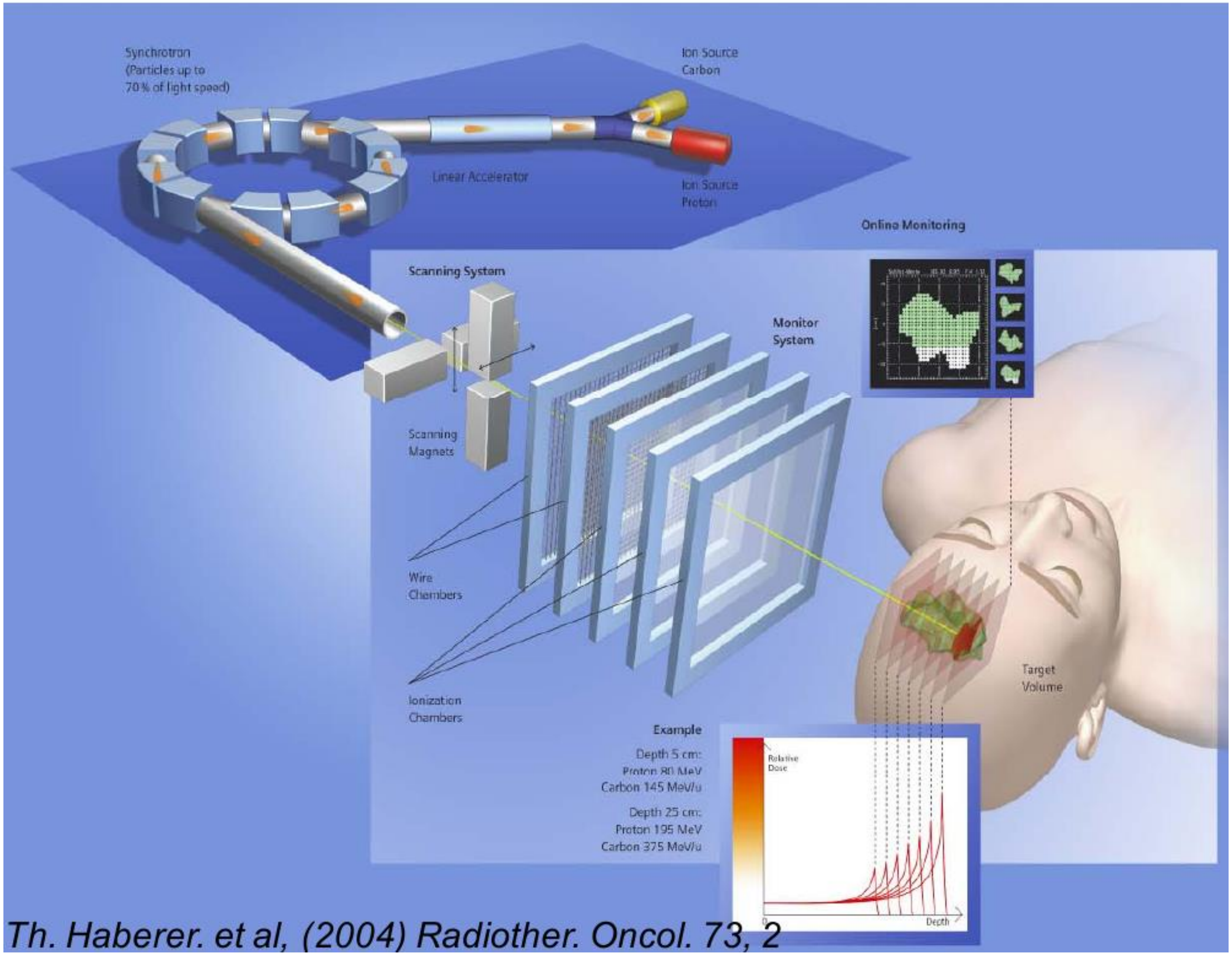
Intensity-controlled magnetic raster scanning



Pencil-like ion beam whose position is precisely controlled by rapid dipole magnets

M. Durante & J. Loeffler., (2010) J. S. Nat. Rev. Clin. Oncol. 7, 37

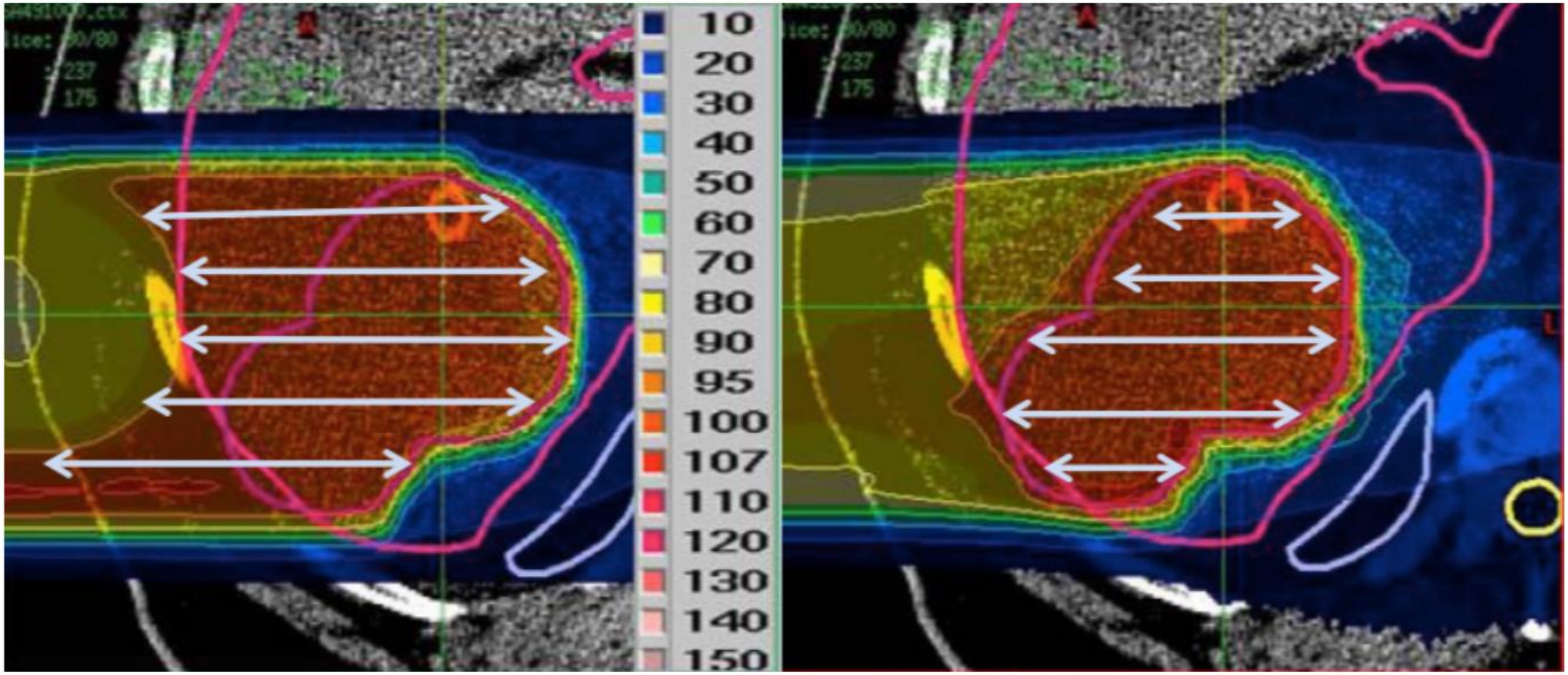
Active Beam Delivery



Th. Haberer. et al, (2004) Radiother. Oncol. 73, 2

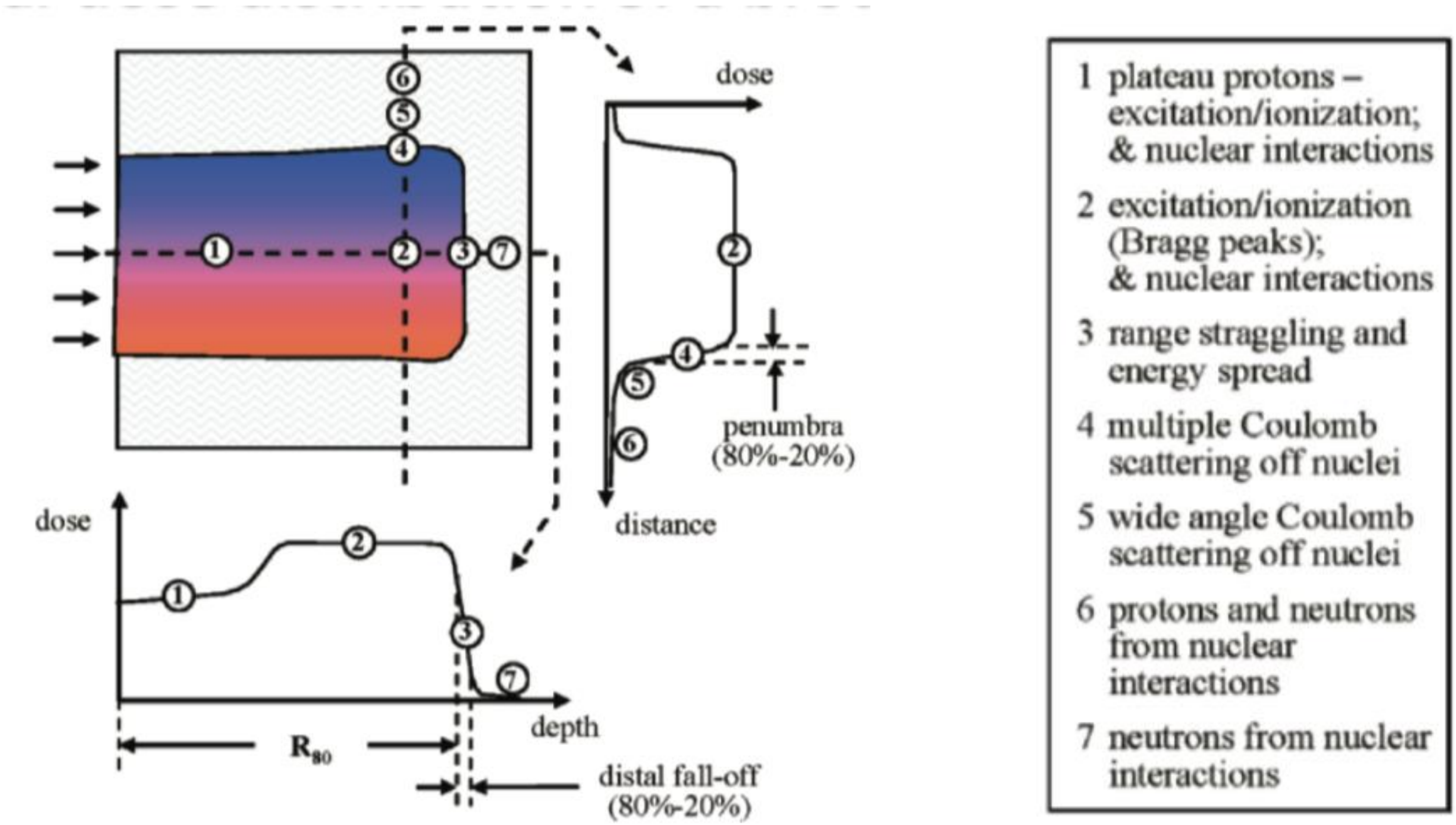
Active vs Passive Beam Delivery

Liver treatment with scanning



(C. Gillmann 2014) O. Jäkel 2018

Schema of principal contributions



Schema of the principal contributions to the dose at several points within and outside the broad beam

M. Goitein 2008

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Any Questions?

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