Tumour Therapy with Particle Beams

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[physics/0004015]

Phy 224B
Chapter 20: Applications of Nuclear Physics
24 March 2005
Roppon Picha

Ion therapy history

- 1946: Robert Wilson (Harvard) proposed use of protons in treating tumors
- 1954: first patient treated with protons at Berkeley
- 1990: first dedicated proton center - Loma Linda University (south CA)
- 1994: first ion center - Chiba, Japan
- 1997: second ion center - GSI Darmstadt, Germany
- 2004: 23 protons centers and 3 ion centers in operation worldwide

Intro

- γ rays are easy to obtain from radioactive sources such as ^{60}Co; electrons can be produced to MeV by inexpensive linear accelerators
  - disadvantages: they deposit energy close to surface
- Charged particles deposit large energy near the end of their trajectories (Braag peak)
  - heavy ions are even superior to protons in treating deep-seated, well-localized tumors, due to ionization increasing with z^2

Energy loss

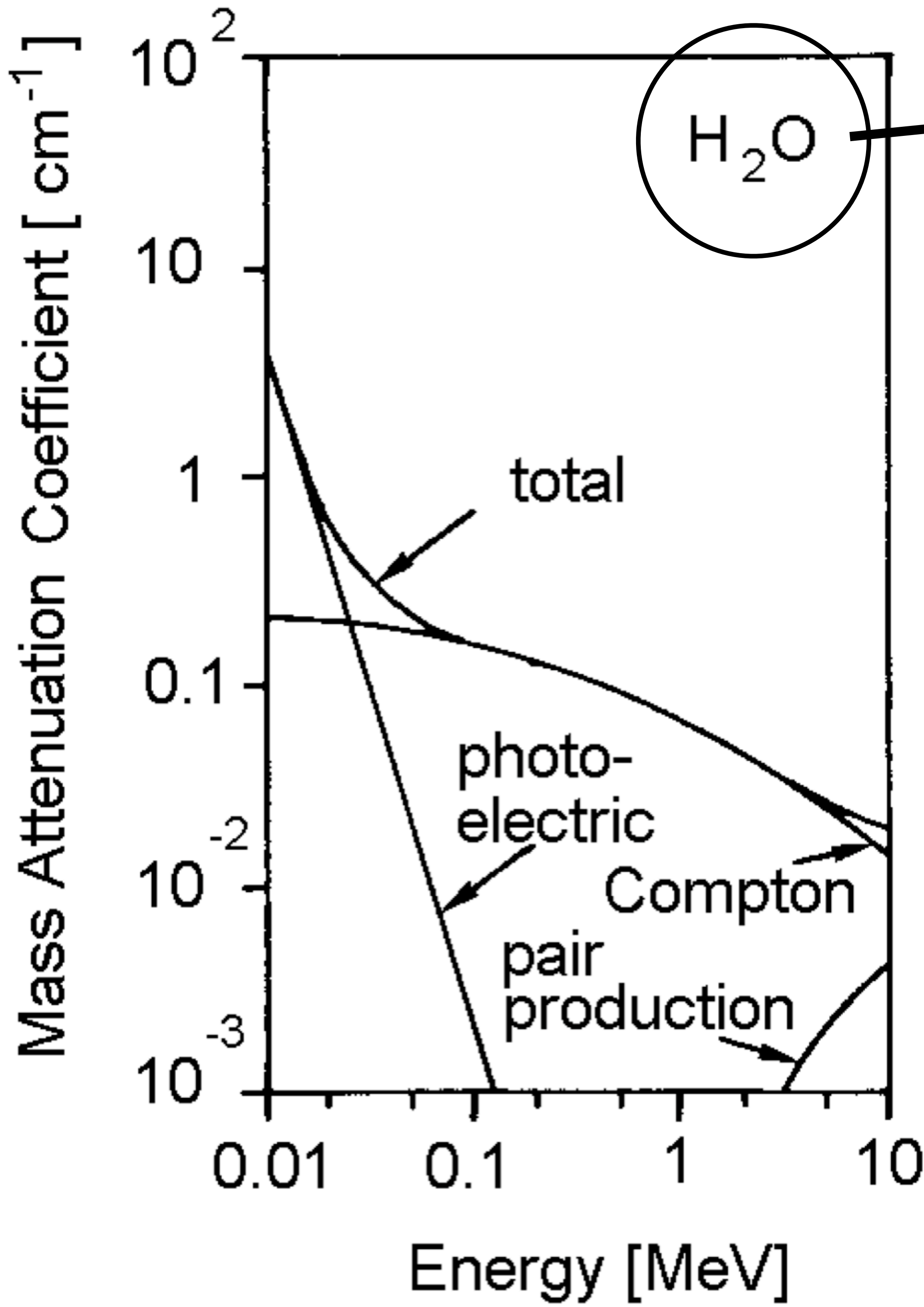
- photon: $I = I_0 e^{-\mu x}$ $\mu = \mu(E, z)$

- charged particle (Bethe-Bloch):

$$\frac{dE}{dx} = 2\kappa \left(\ln \frac{E_{kin}^{max}}{I} - \beta^2 - \frac{\delta}{2} \right)$$

$$\kappa \propto z^2 \frac{Z}{A} \cdot \frac{1}{\beta^2}$$

photon mass attenuation



human body ~ 60% water

Fig. 1: Mass attenuation coefficient for photons in water as a function of the photon energy

mass attenuation coefficient:
= (interactions per thickness)/ density
~ degree of energy loss

energy loss of charged particles

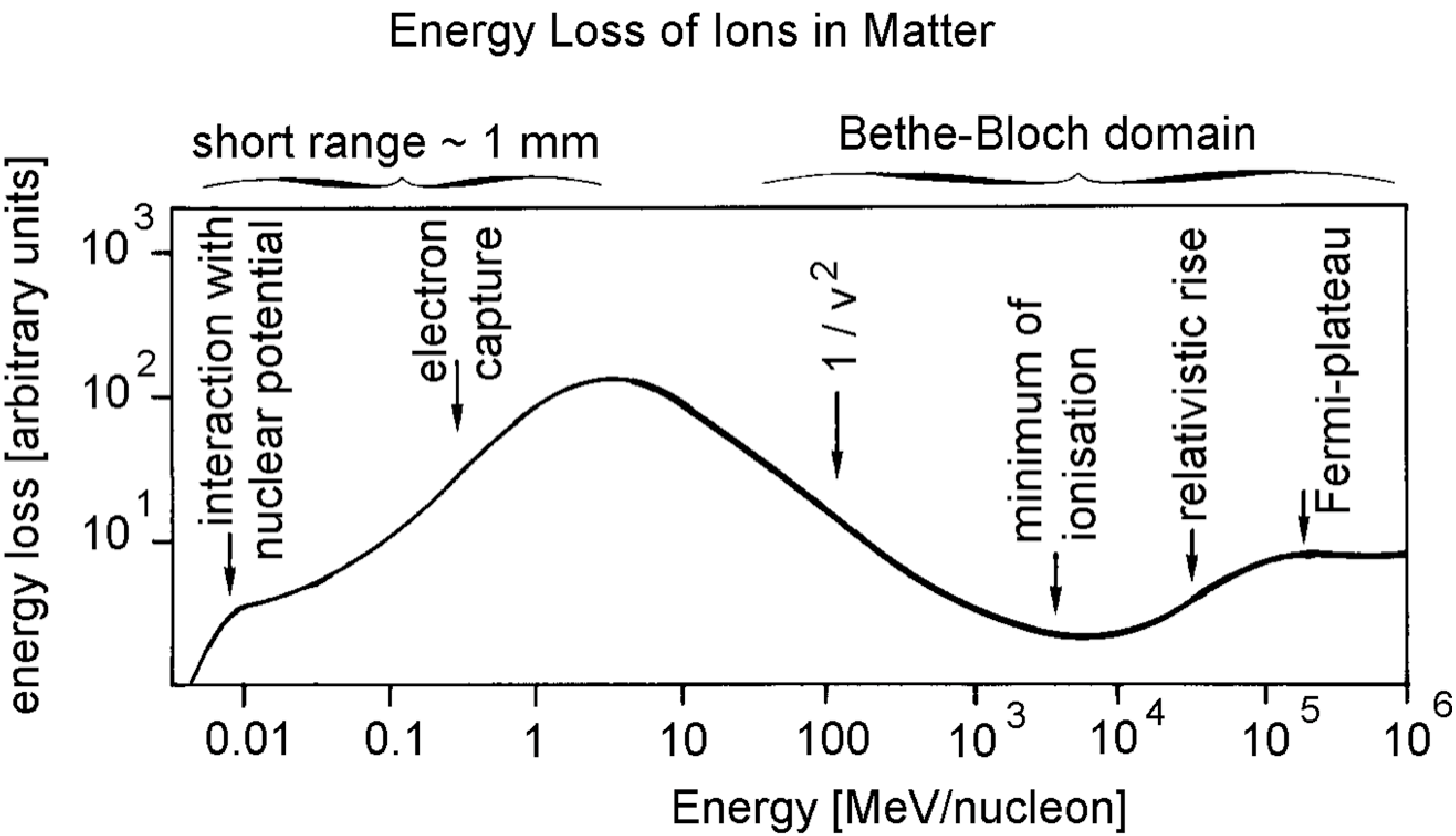


Fig. 2: Energy loss of ions in matter as a function of their energy

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depth and incident energy

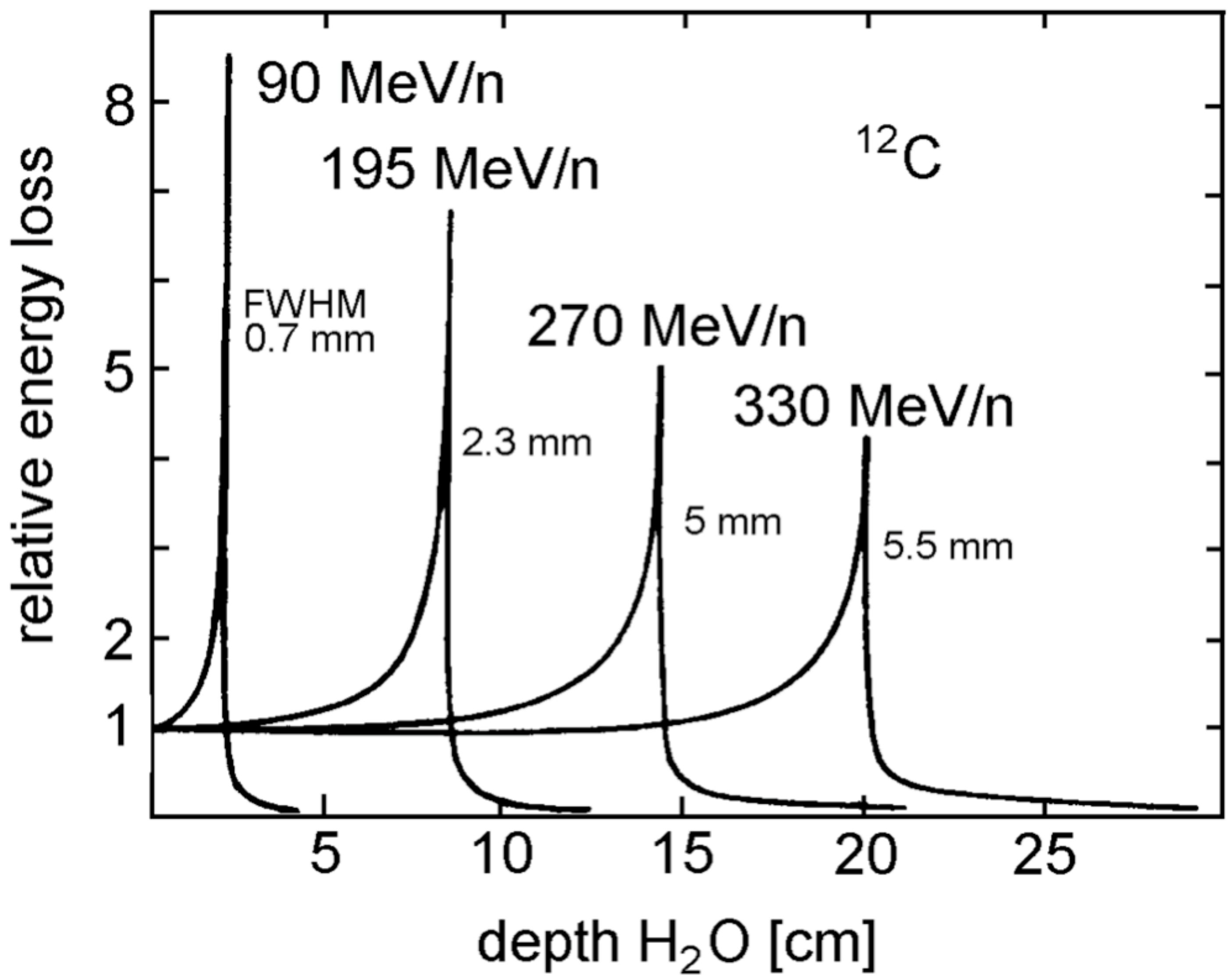
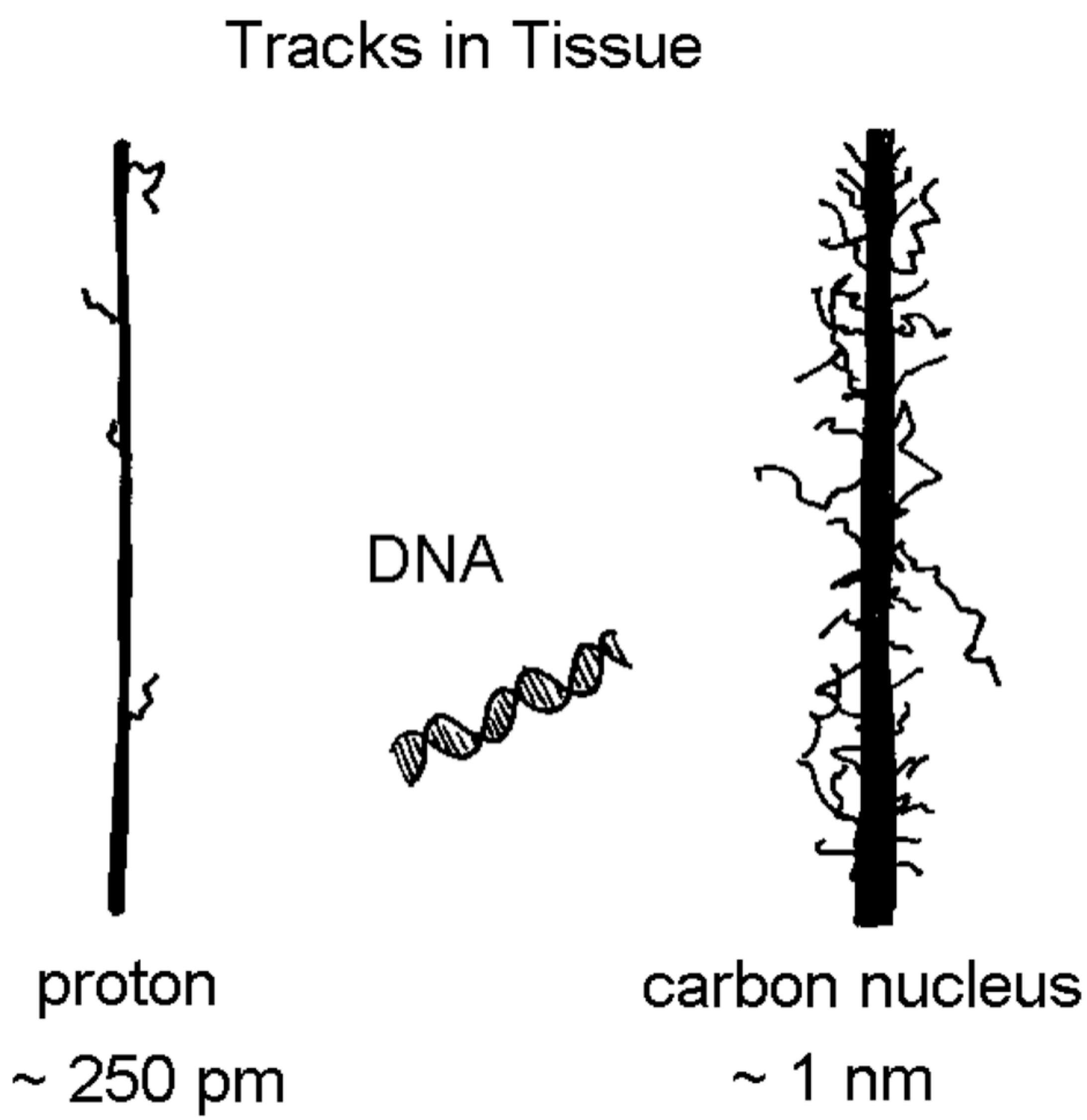


Fig. 3: Energy loss of carbon-ions (^{12}C) in water as a function of depth

Bragg peak depth increases with energy



higher Z, higher degree of ionization

Fig. 4: Sketch of a proton and a carbon nucleus track in tissue. The fuzziness of the tracks is caused by short range δ-rays

(δ-rays = electrons ejected from ionization)

Carbon advantages

- Carbon’s radiation damage is repairable to a large extent in the entrance channel of the beam, and becomes irreparable only at the end of the beam's range - in the tumor itself.
- lighter particles such as protons cause fewer double-strand breaks in DNA than heavier ones like carbon.
- Carbon ions do not scatter as much as lighter particles.
- Heavier ions, such as ^{10}Ne, tend to fragment. Carbon does fragment too but its fragmentation products can be detected by PET.

source: “GSI treats cancer tumors with carbon ions”
CERN Courier, vol 38, no 9

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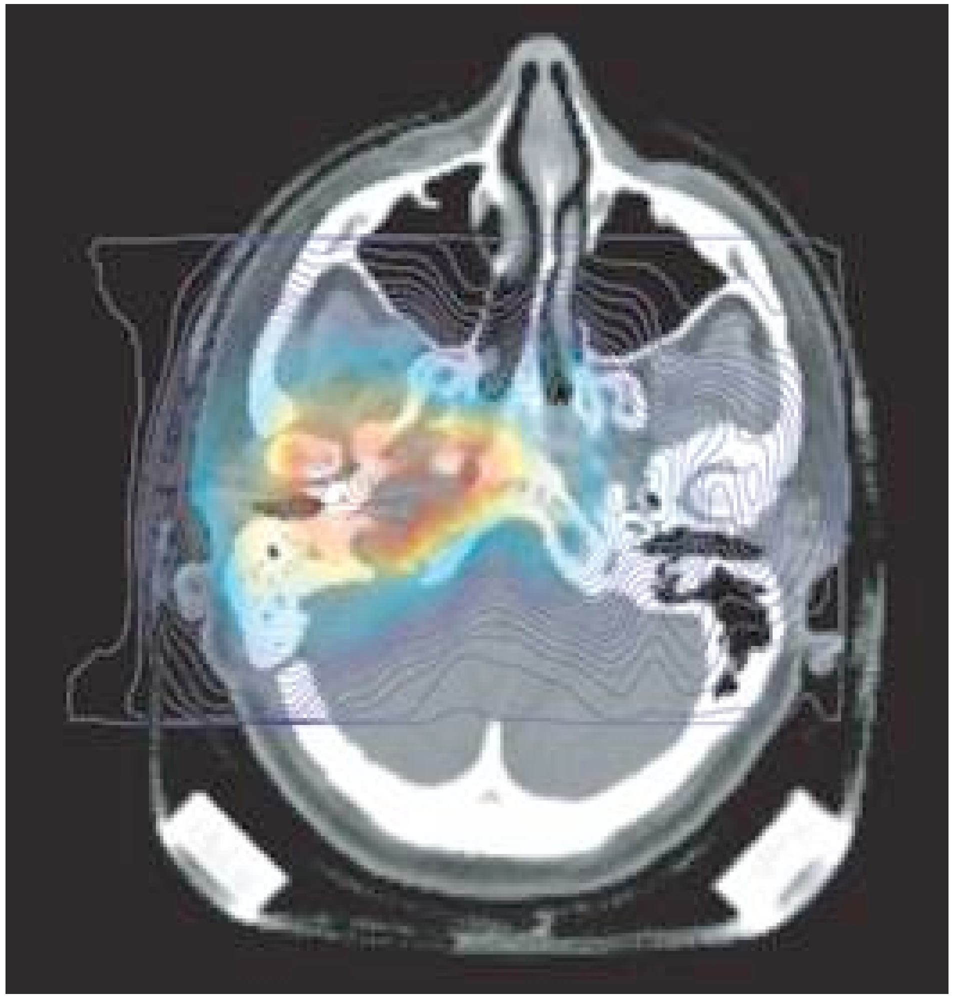
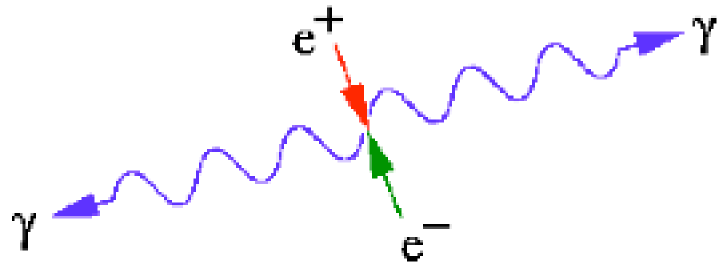
Positron Emission Tomography

- part of ^{12}C ions fragment into lighter ^{11}C and ^{10}C ions. these ions emit positrons.
- PET = $e^+ + e^- \rightarrow 2\gamma$
- PET allows "live" beam monitoring





Production of particle beams

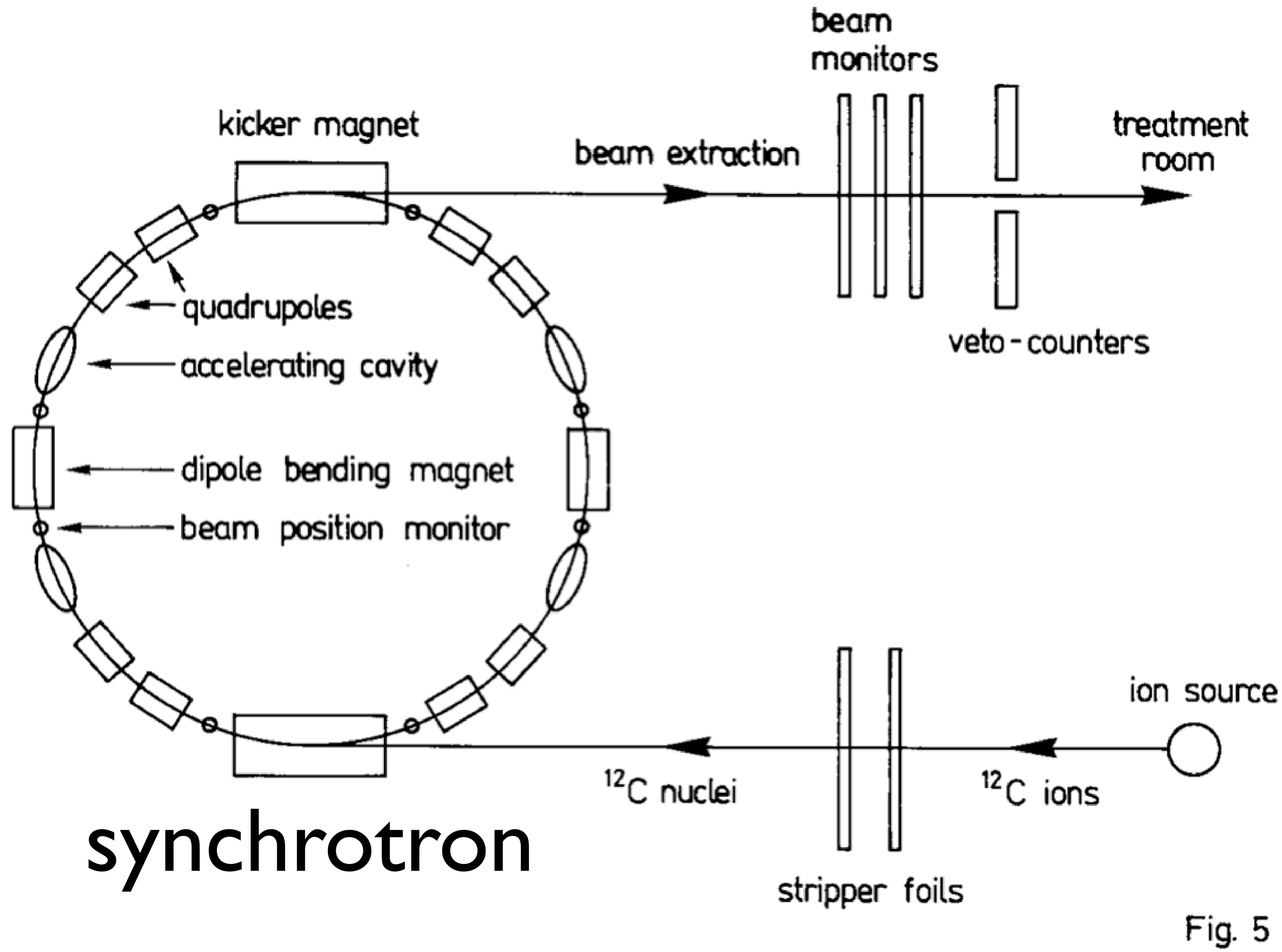


Fig. 5: Sketch of a typical set-up for the acceleration of heavy ions (not all components are shown)

only p shows Bragg peak

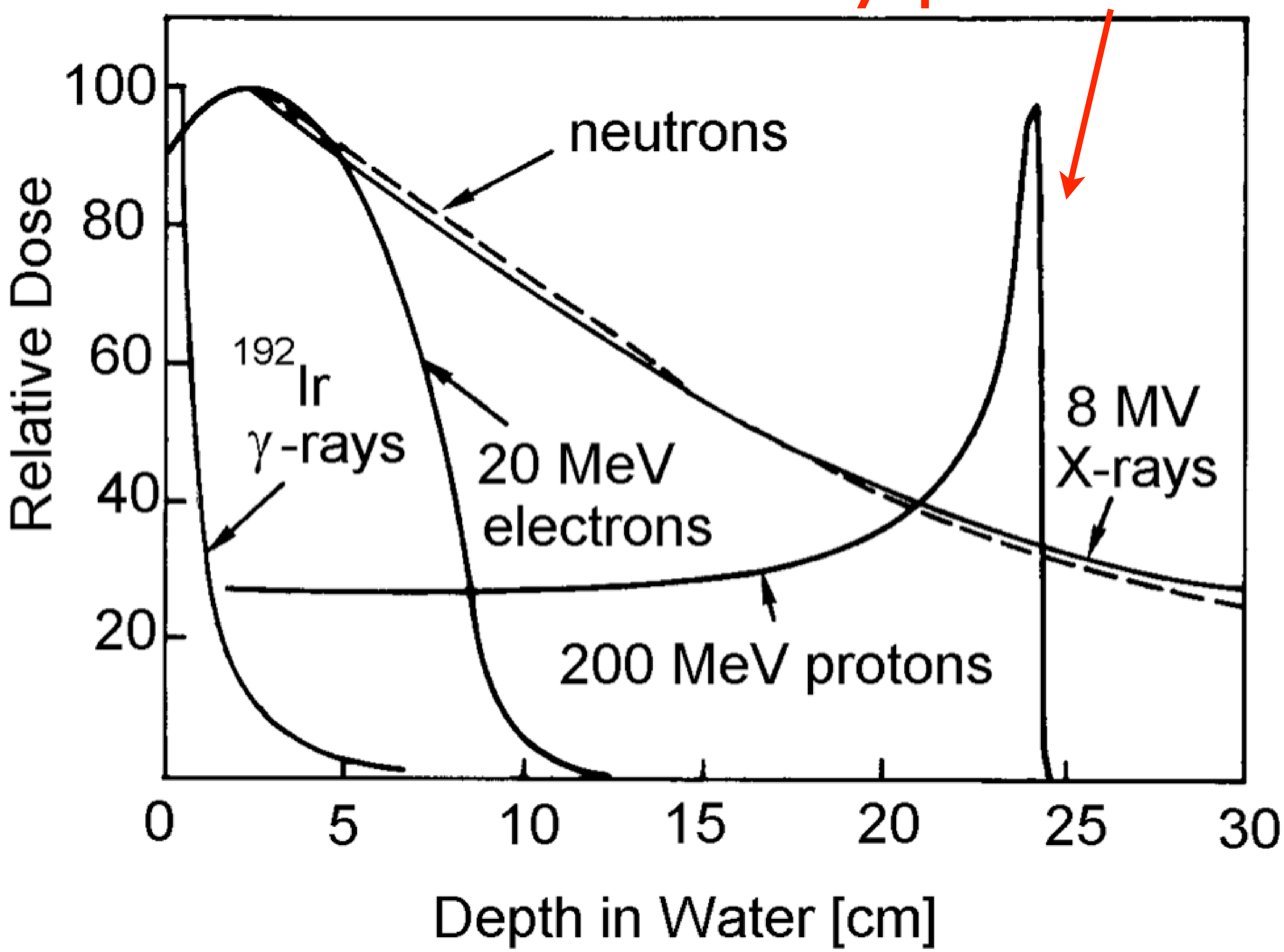
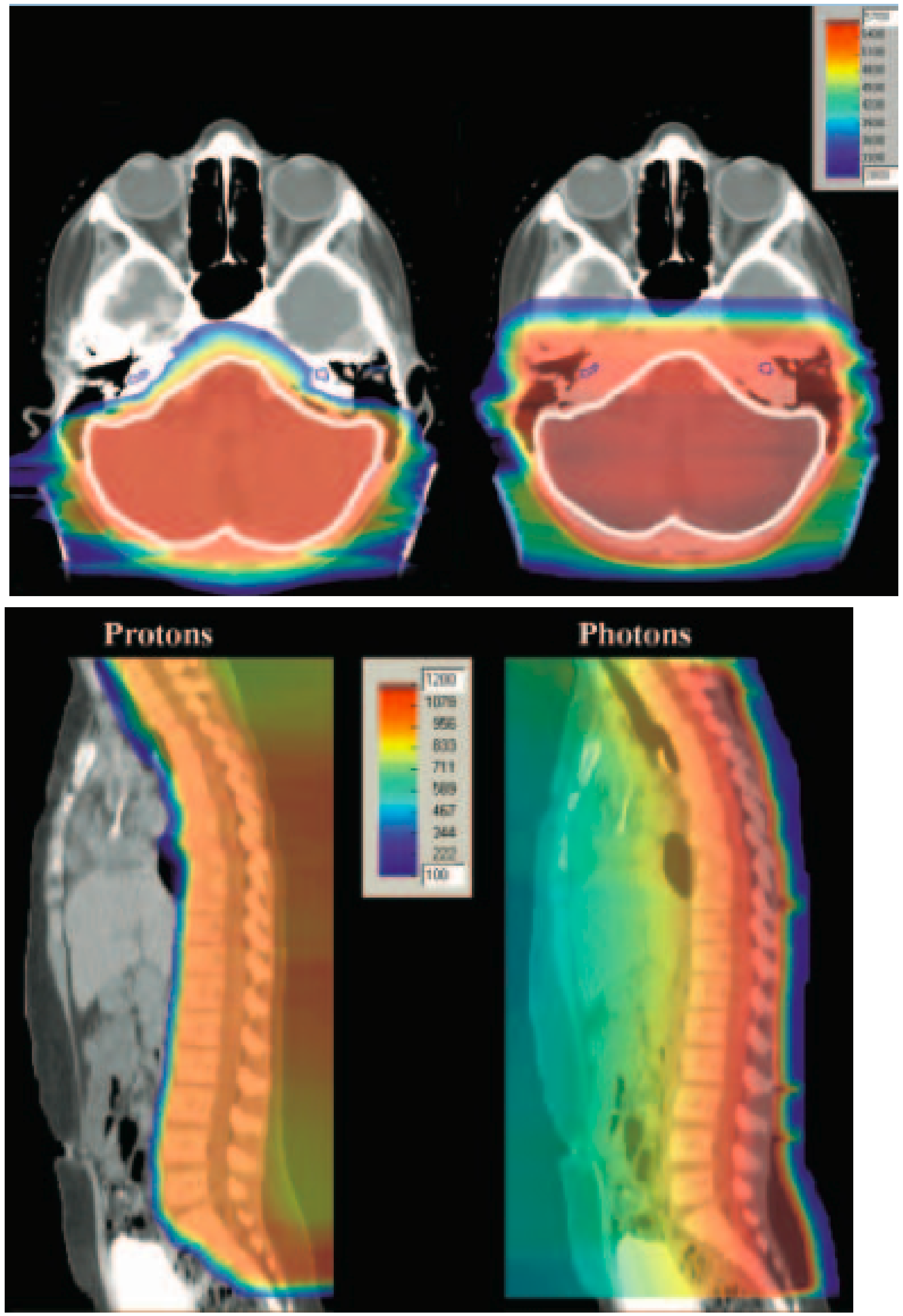


Fig. 6: Comparison of depth-dose curves of neutrons, γ-rays (produced by a 8 MV driven X-ray tube), 200 MeV protons, 20 MeV electrons and ^{192}Ir-γ-rays (161 keV)

protons vs. photons



- protons cause less damage on entrance (low plateau)
- deposit more energy on deep-seated target (Bragg peak)

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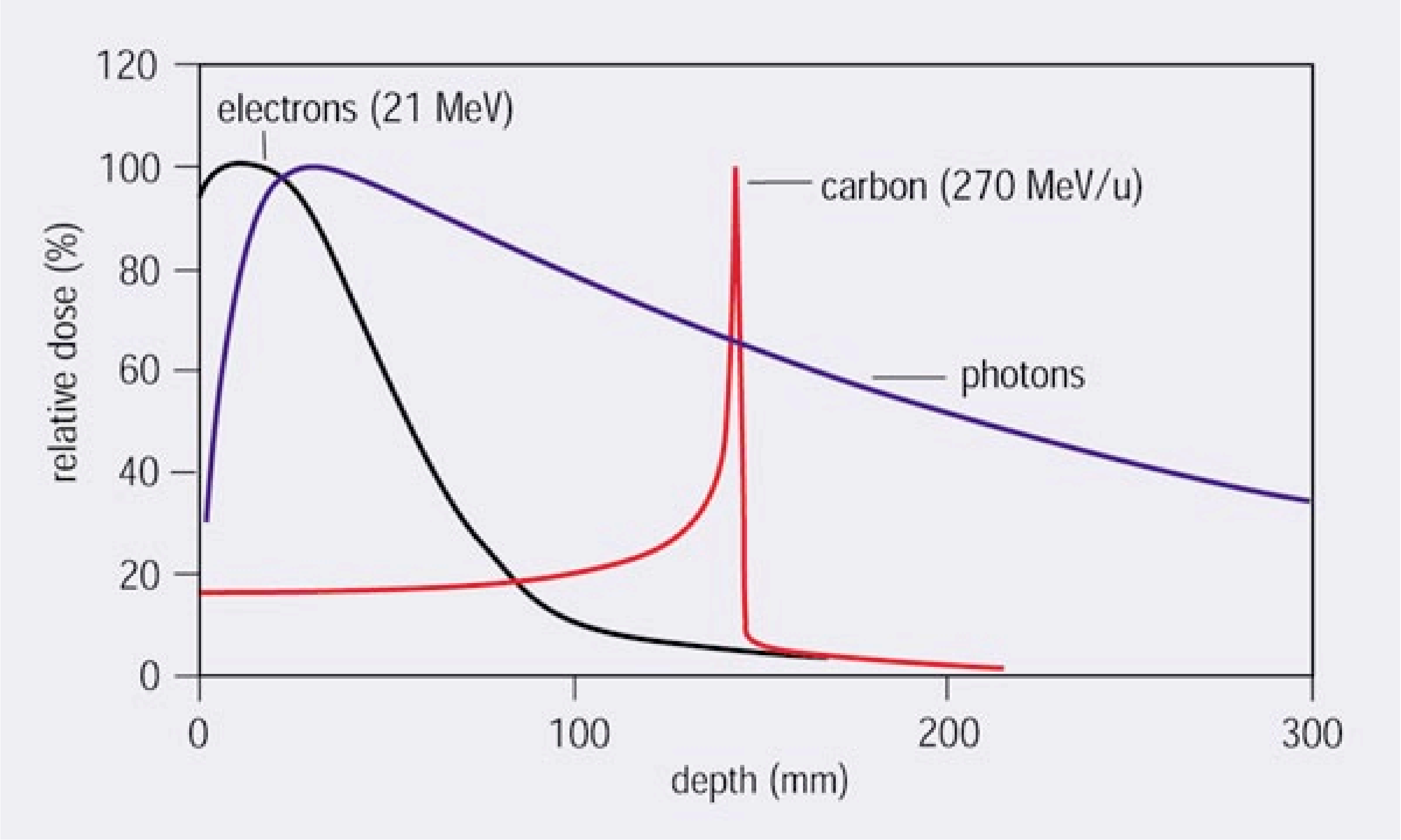
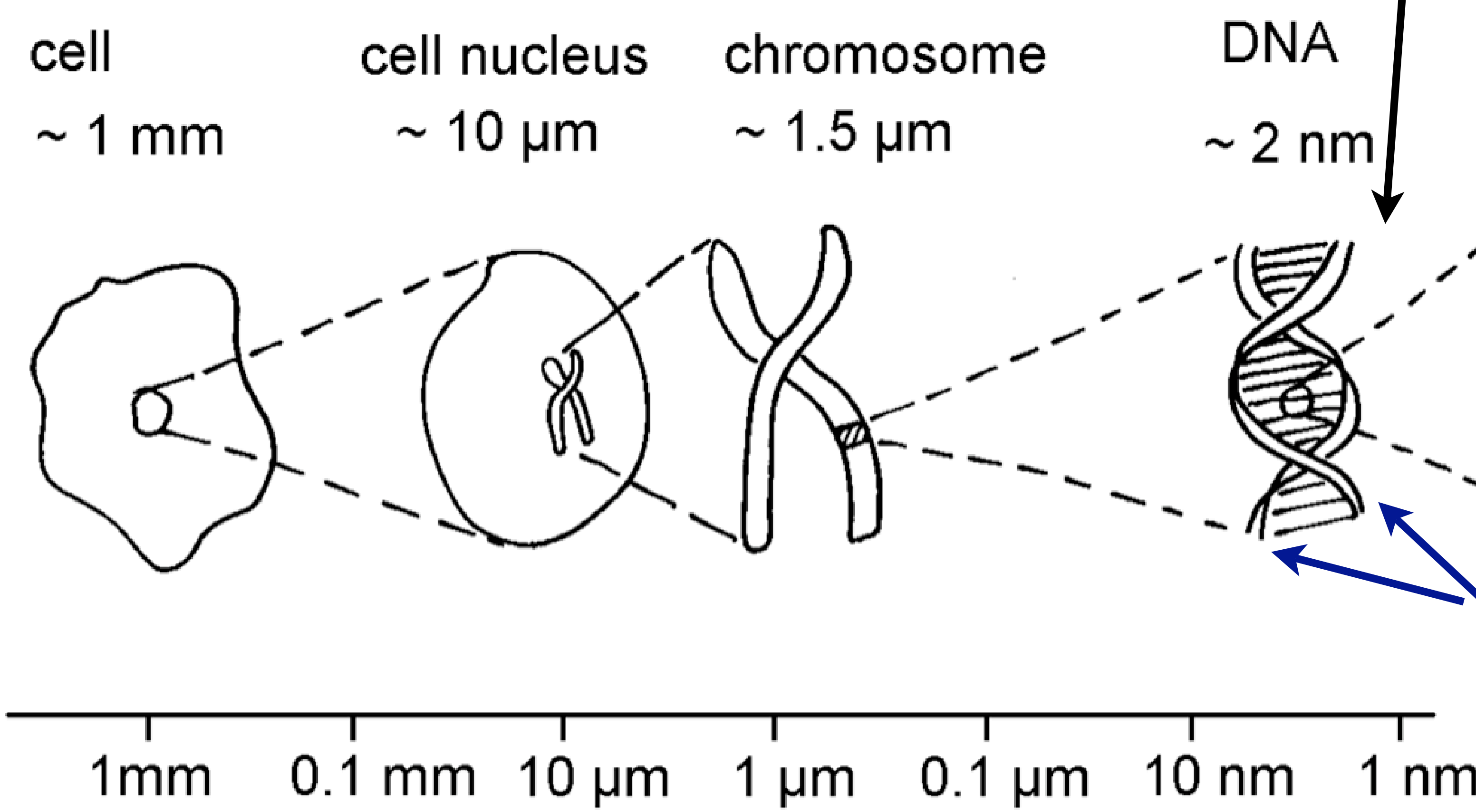
relative dose



window in a church near GSI (Wixhausen)

target is the cell's DNA

Fig. 7: Sketch of typical dimensions of biological targets



2 identical strands. if one breaks, cell can repair itself.

carbon ions are suited to destroy both strands. heavier ions can cause too much irreparable damage to surrouding tissues

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Raster scan

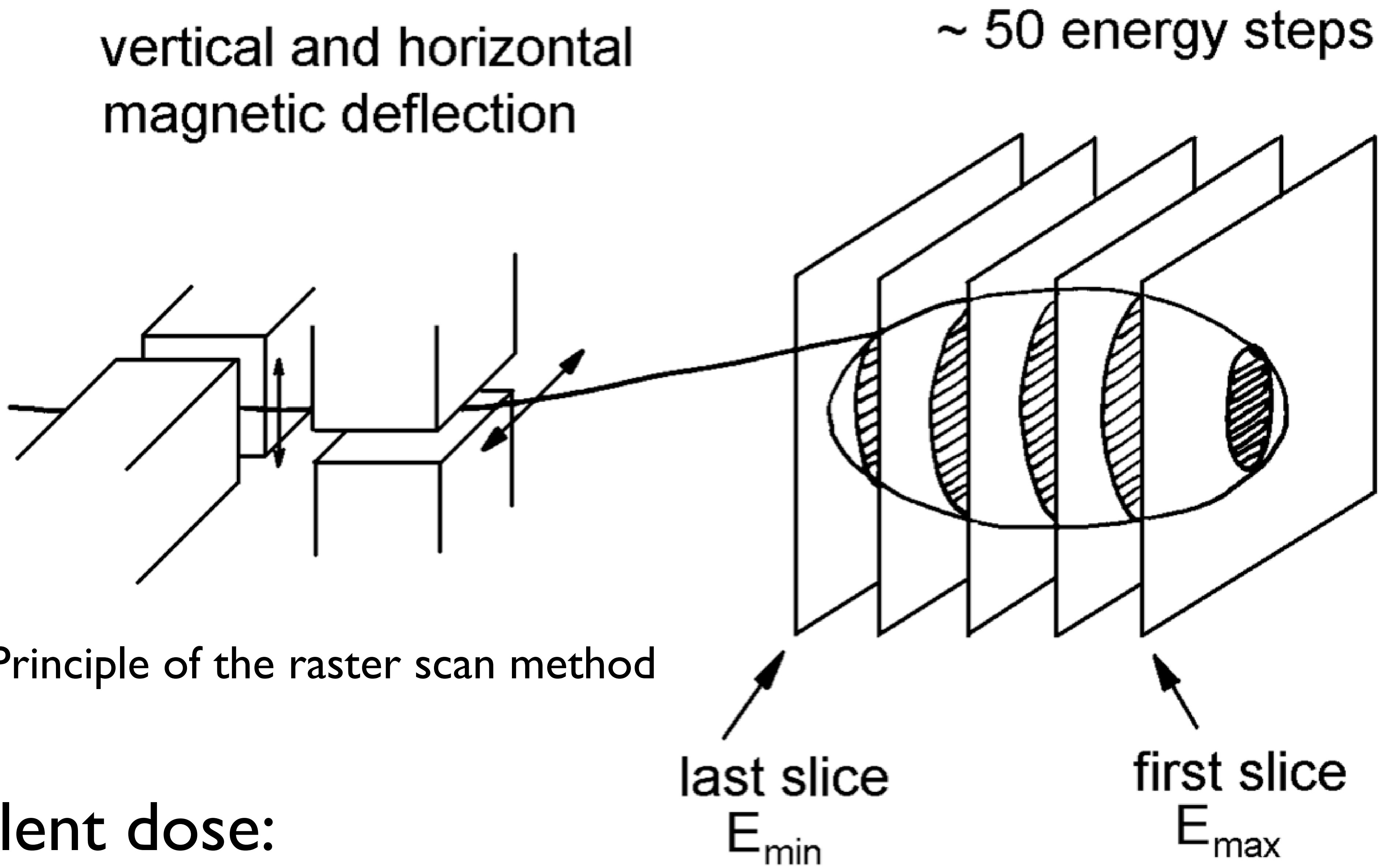


Fig. 8: Principle of the raster scan method

equivalent dose:

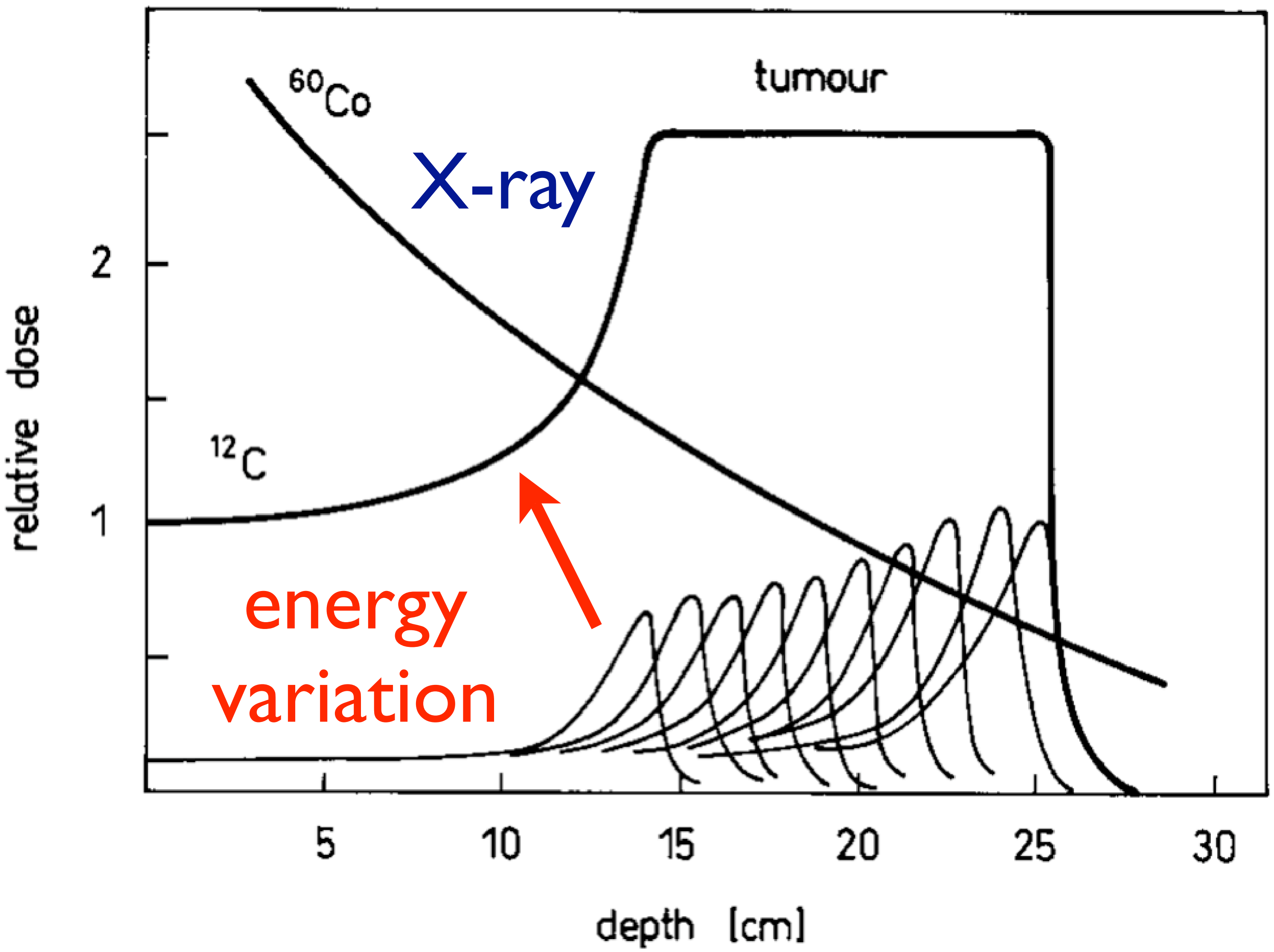
$$H = \frac{1}{\text{tumor mass}} \int \frac{dE}{dx} dx \cdot RBE$$

is calculated for every voxel (3-d pixel)

for tissue depth of 2 to 30 cm, we need energies from 80 to 430 MeV/nucleon

Raster scan animation

http://www.gsi.de/portrait/Broschueren/Therapie/RasterScan.mpg



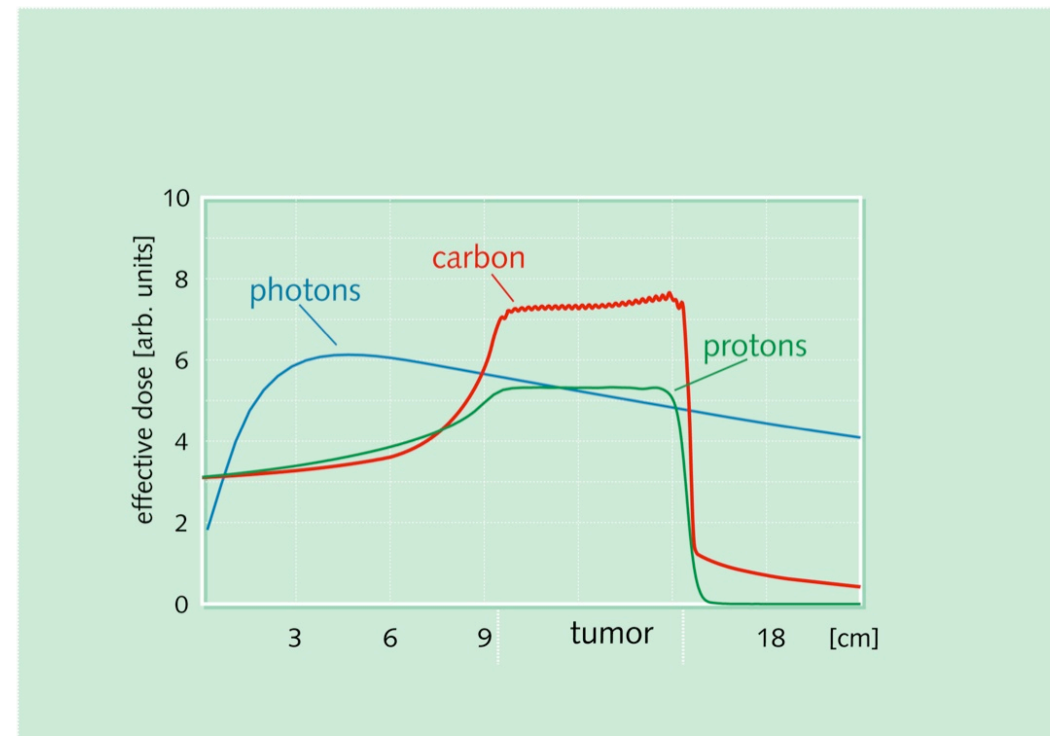
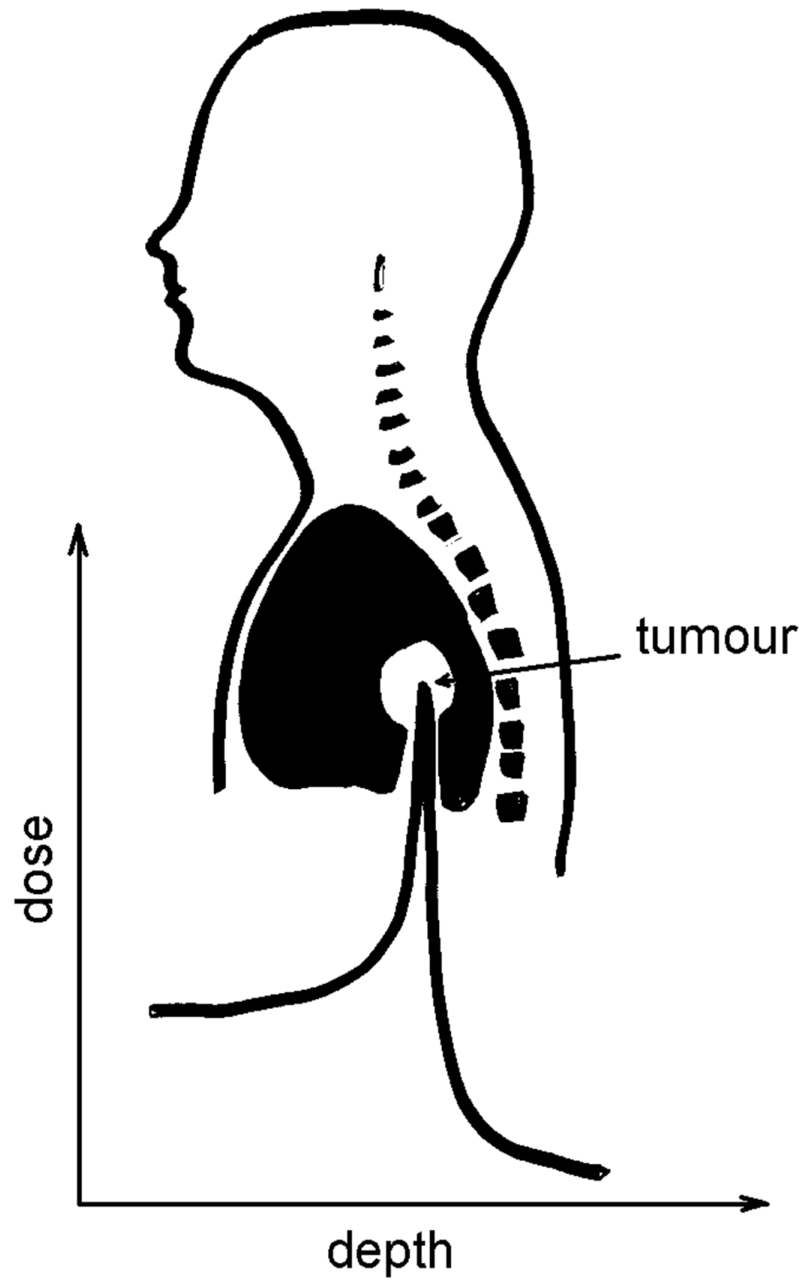
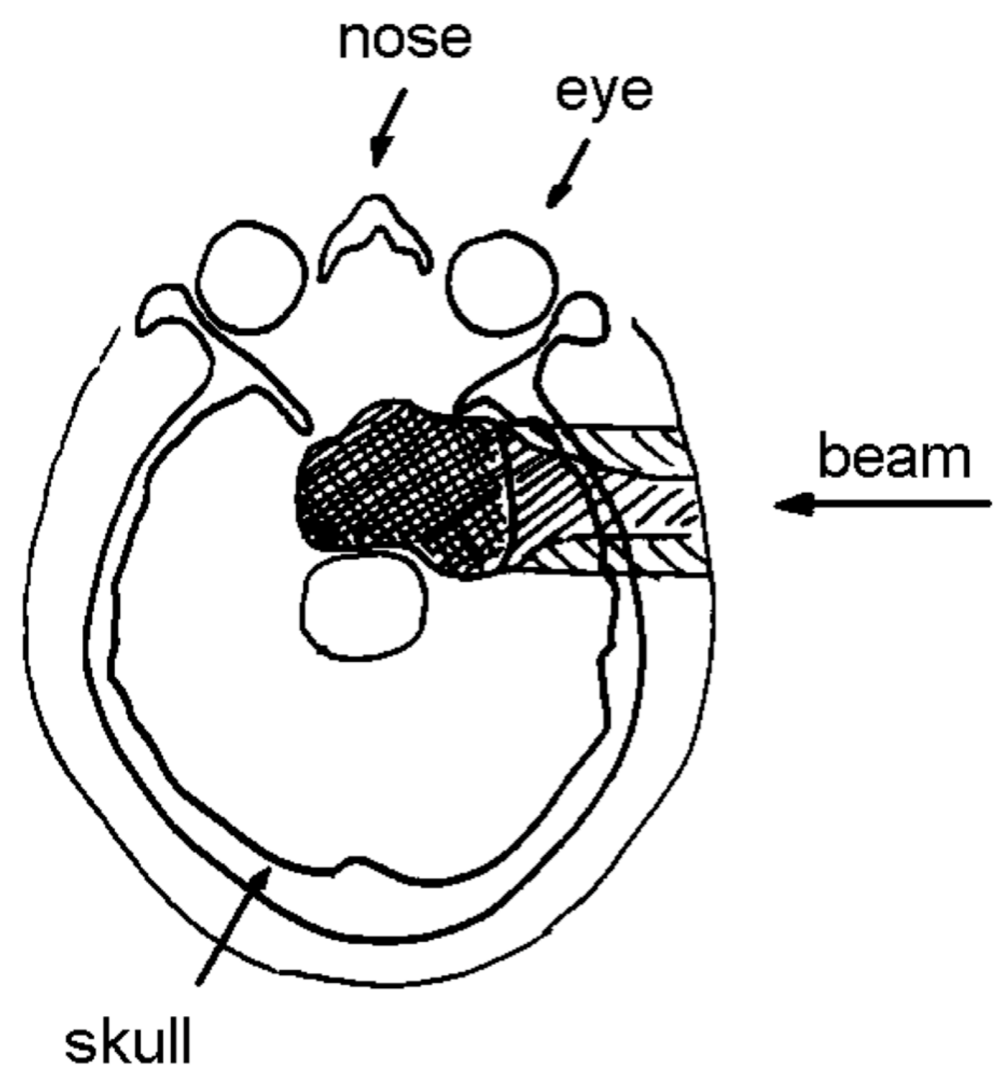


Fig. 9: Superposition of Bragg-peaks by energy variation

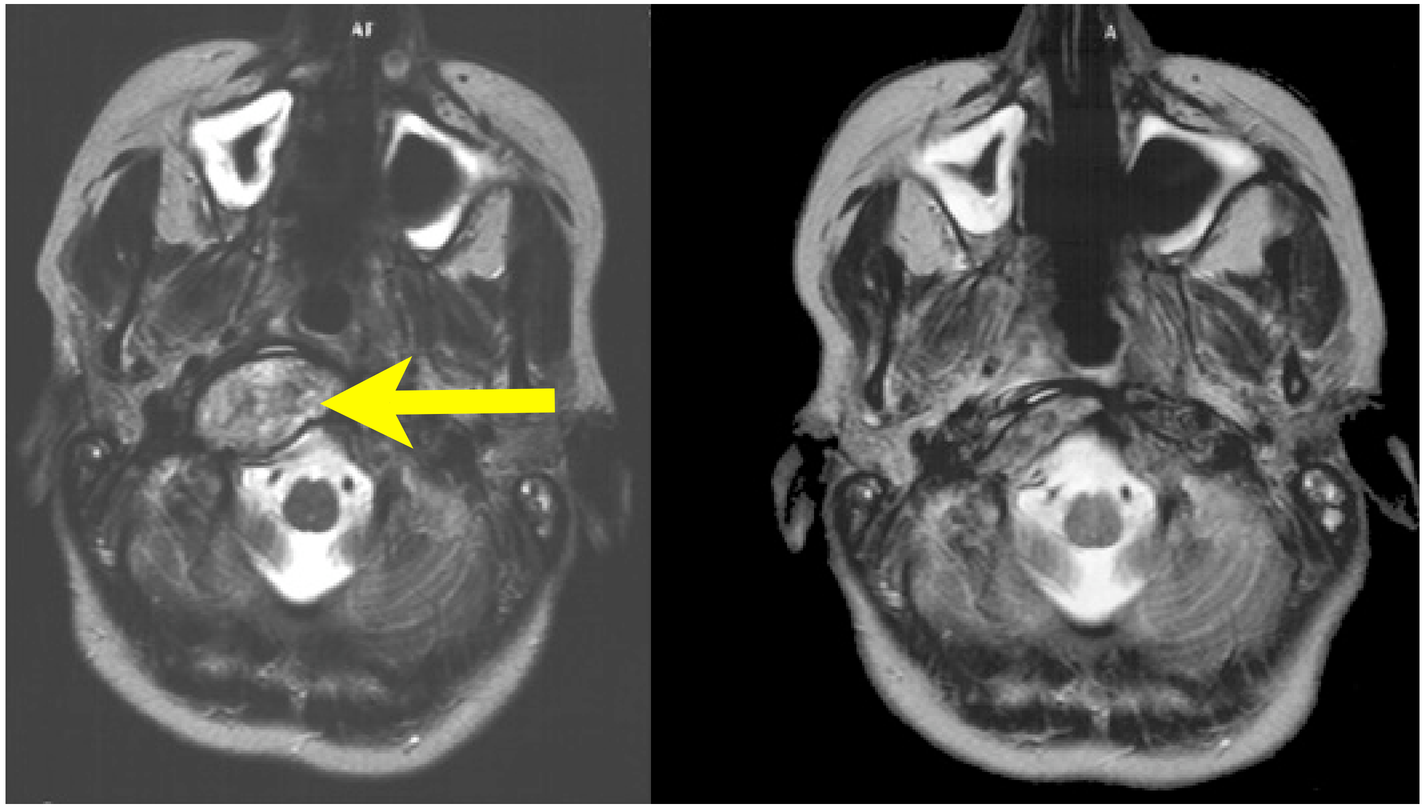


The position of the Bragg-peak can be adjusted by energy selection to produce a maximum damage at the tumor site (here in the lung)

Fig. 10:



Mapping of a brain tumor with ionisation from heavy ions. Some damage at the entrance region cannot be avoided



before and after 6 weeks of carbon therapy
(at GSI)

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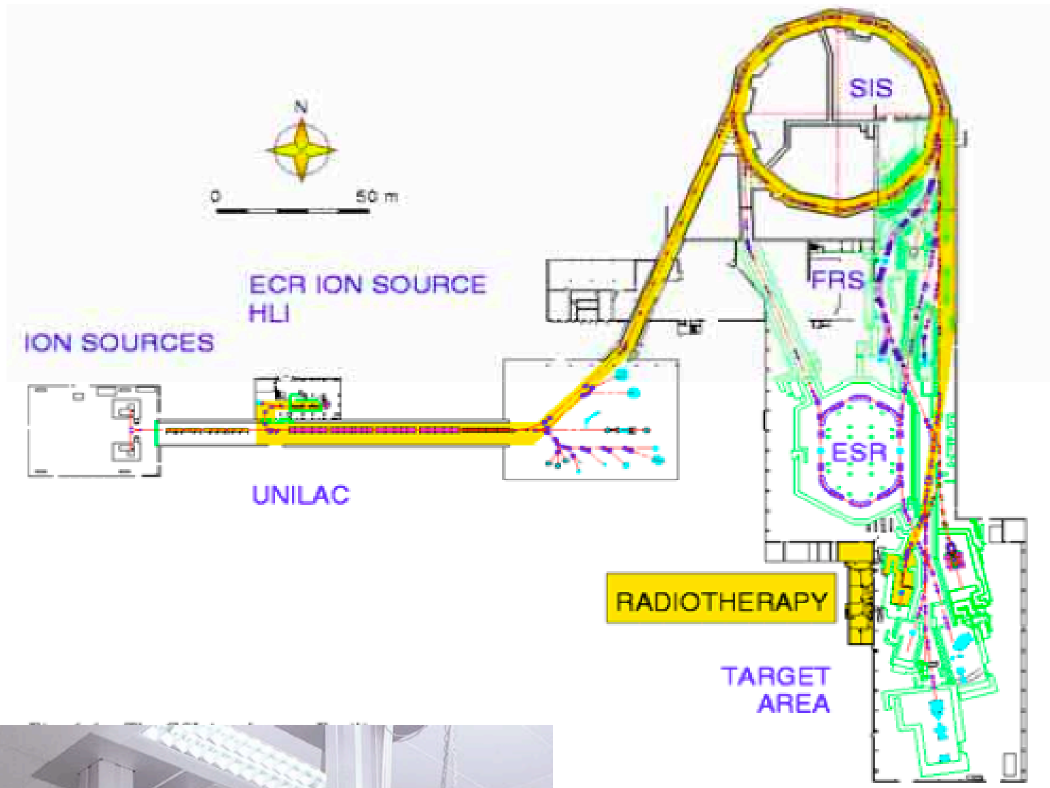
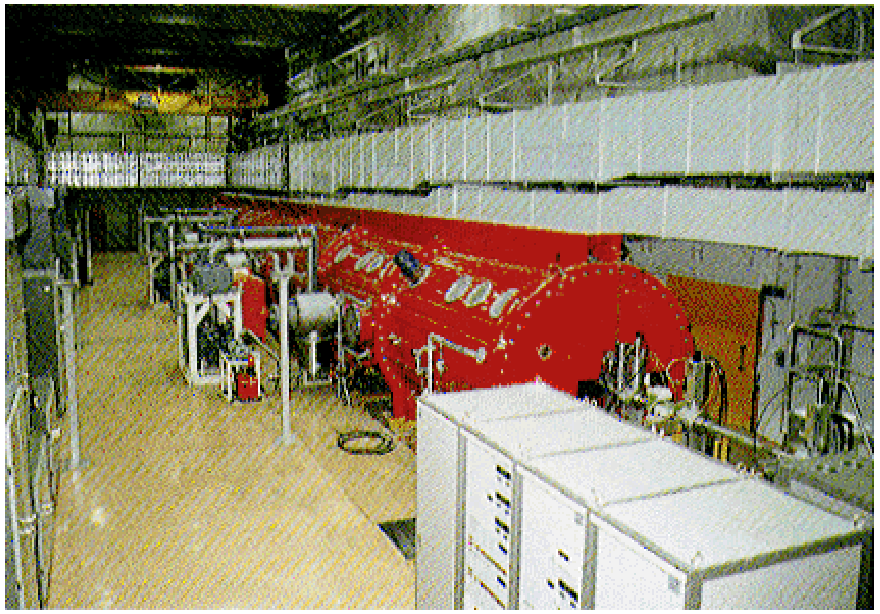
Current heavy ion facilities



GSI, Darmstadt, Germany

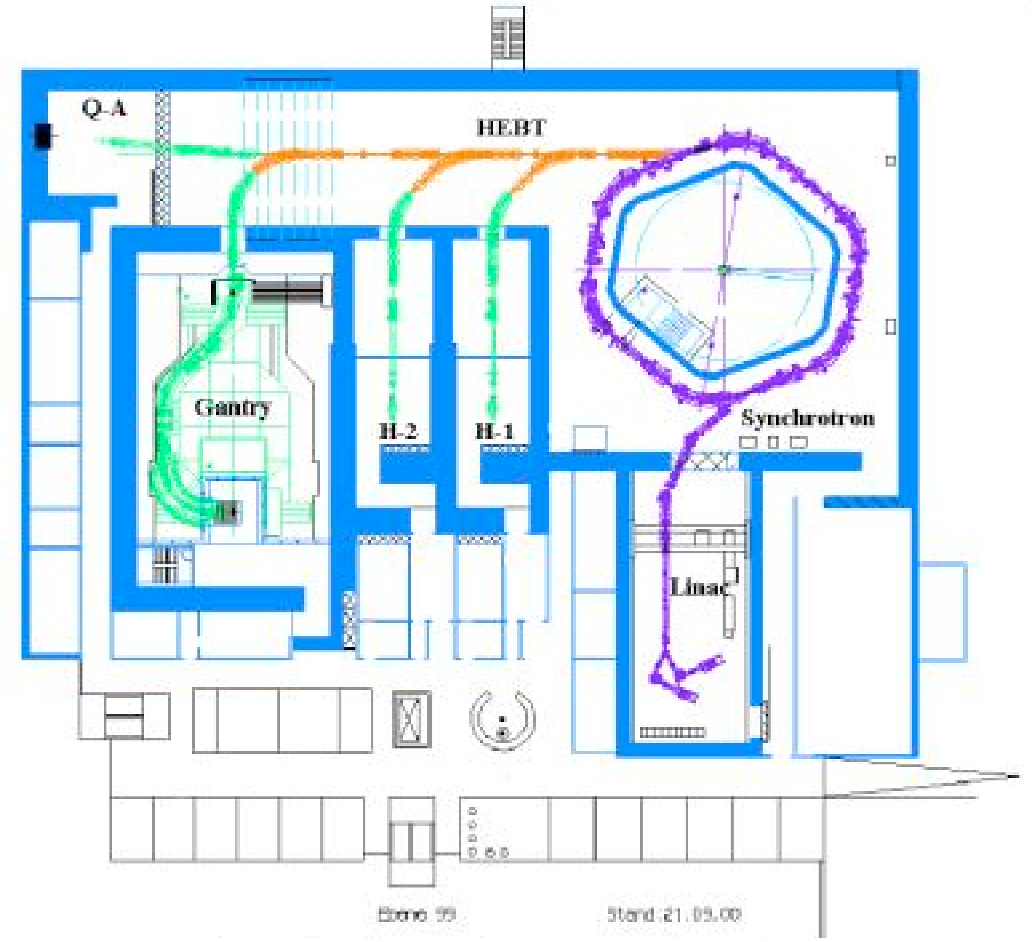


HIMAC, Chiba, Japan

HIBMC, Hyogo, Japan

Planned projects

- HICAT (**H**eavy **I**on accelerator light ion **CA**ncer **T**reatment) - University Clinic Heidelberg, Germany - 2007



- **E**uropean **N**etwork for **LIG**ht ion **H**adron **T**herapy (ENLIGHT) - 2006 -2008

Enlight

Summary

- dE/dx profiles of charged particles make possible to design precise particle beams to treat tumors.
- heavy ions are suitable and effective for well localized tumors.
- Carbon ions open up treatment possibilities of difficult tumors, and complement proton therapy.
- Protons, however, will remain important for many kinds of cancer as well as for treatment of benign (non-cancerous) tumors.