Medical Applications of radiation physics

Riccardo Faccini
Universita' di Roma "La Sapienza"

Outlook

- Introduction to radiation
  - which one ?
  - how does it interact with matter?
  - how is it generated?
- Diagnostics and nuclear medicine:
  - Diagnostics (radiography, SPECT, PET,…)
  - Molecular radiotherapy
  - Radio-guided surgery
- Particle beams in medicine
  - Radiotherapy
  - hadrotherapy

Introduction to radiation

Which one ?
How does it interact with matter?
How is it generated?

Radiation of interest

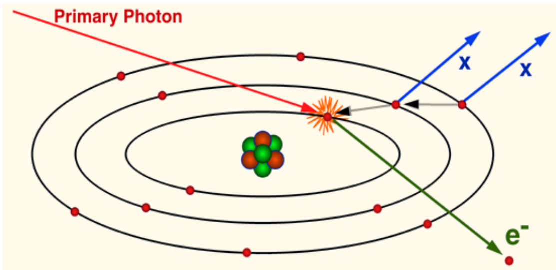
Neutral particles:
High penetration before interacting
Gamma rays: produce electrons
Neutrons: produce low energy protons → more "aggressive"

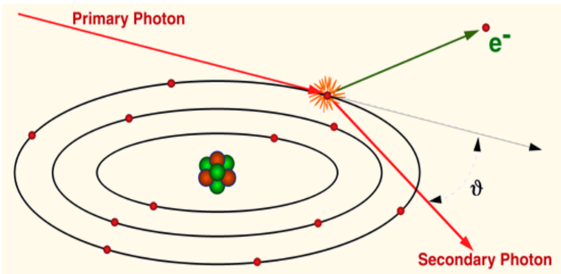
positrons: positrons annihilate with e- and produce 2 photons that escape patient and interact outside

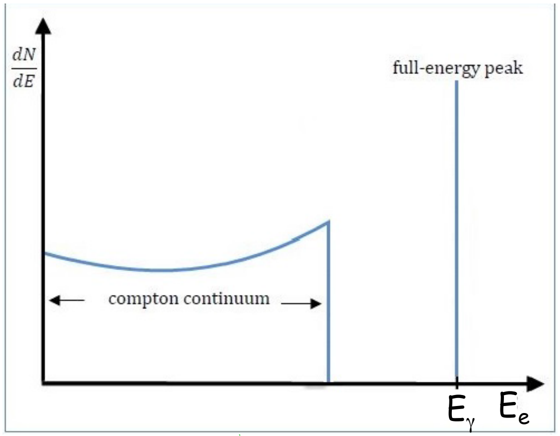
Other charged particles (electrons, protons, ions):
low penetration, short path, depending on energy

gamma- matter interactions

Gamma rays







- Photoelectric effect

Emission of electron with same energy as impinging photon

- Compton scattering

Only part of the energy is transferred to an electron

→ photon "remnant" with lower energy and different direction

- Pair production

$\gamma\gamma \rightarrow e^- e^+$ (only if $E_\gamma > 2m_e$)

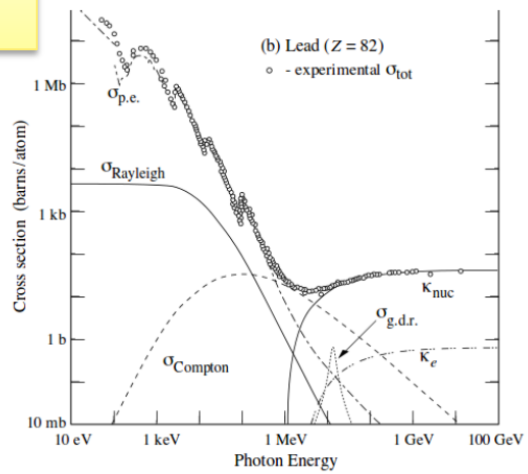
gamma-matter interactions (II)

A photon survives unchanged until it interacts → then it transforms

Photon beam attenuates exponentially

μ=coefficiente di attenuazione
σ=sezione d'urto
n= # atomi per unita' di volume

$$N(x)=N(0)e^{-\mu x}=N(0)e^{-n\sigma x}$$

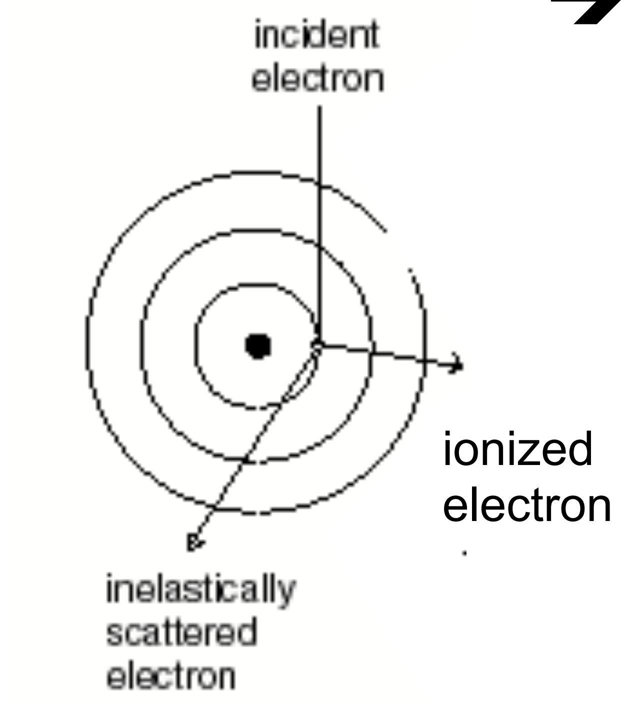


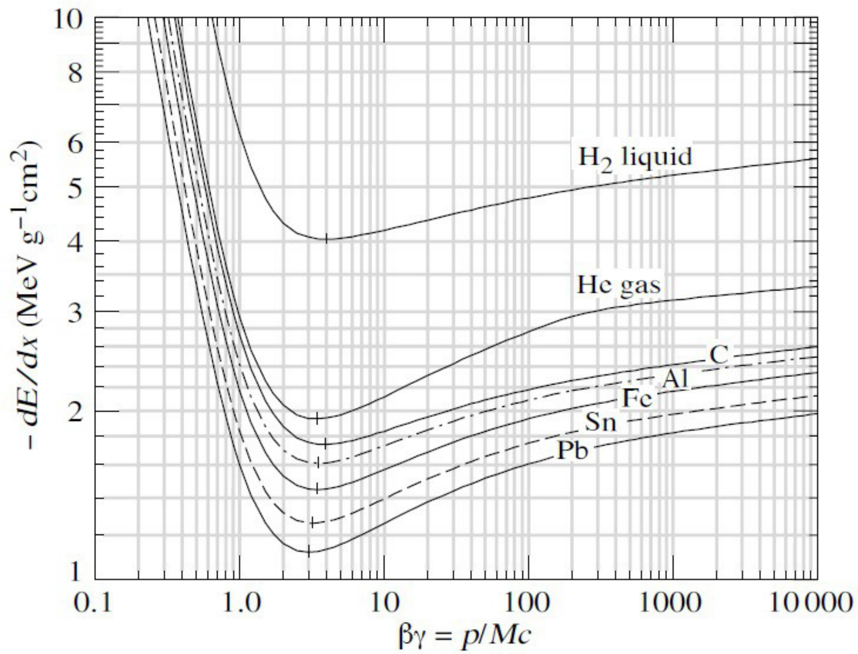
$\sigma_{tot}=\sigma(p.e.)+$
$\sigma(compton)+$
$\sigma(pair)$

Charge particles-matter interactions

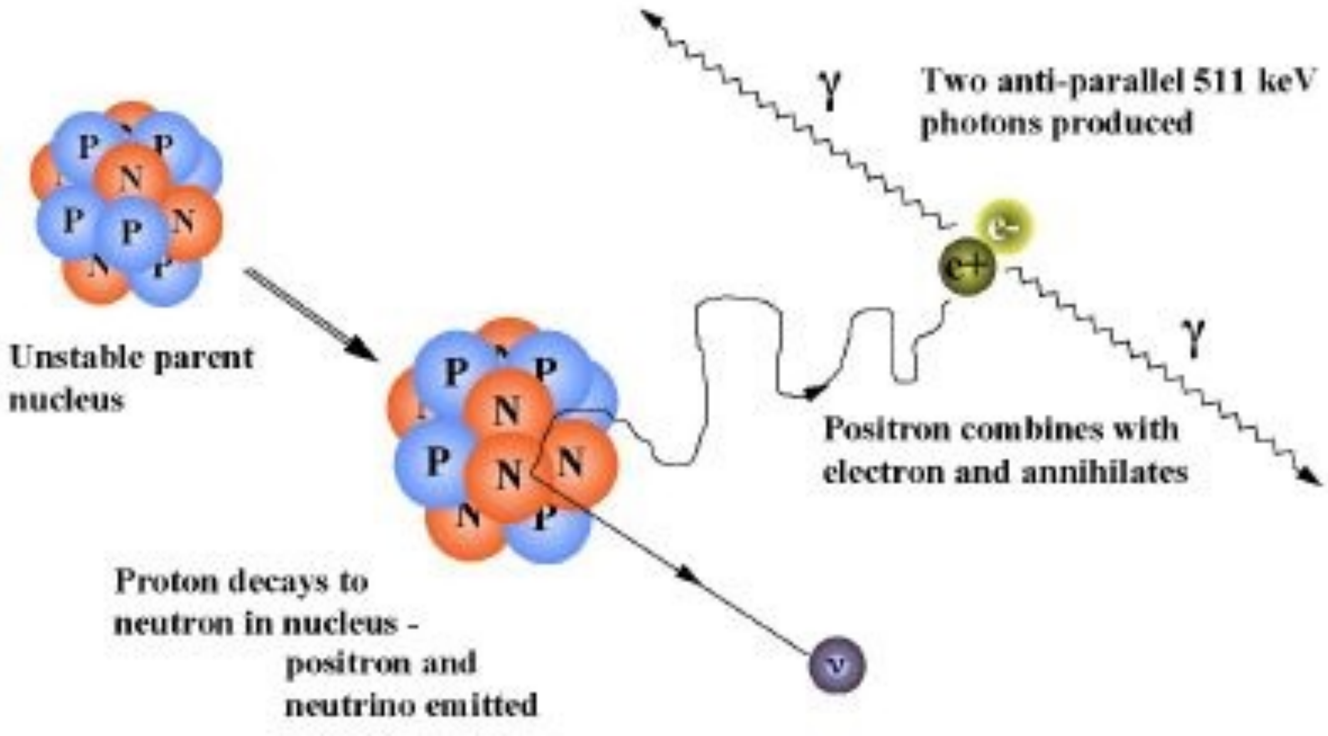
Dominant interaction: ionization

→ continuous release of energy until particle stops





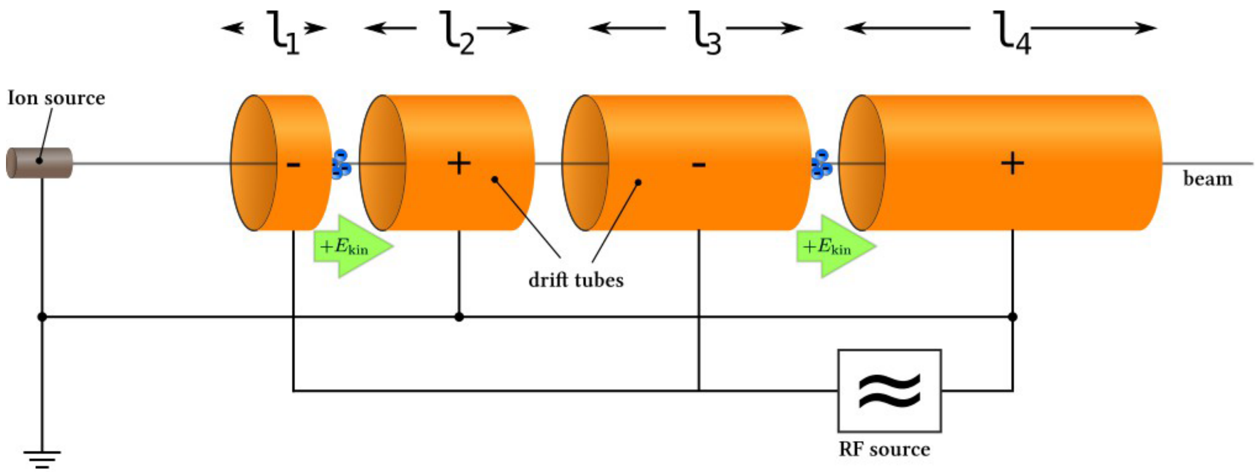
positron-matter interactions



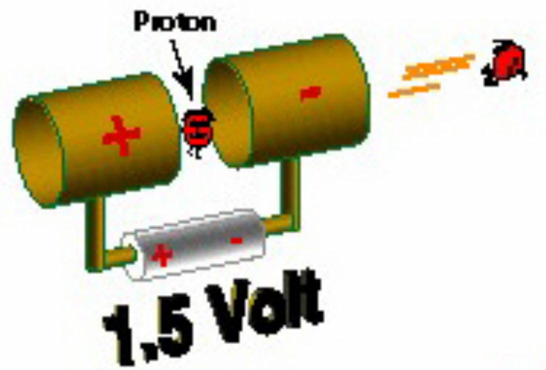
In 80% of the cases there are two back-to-back mono-energetic photons

Accelerators: LINAC

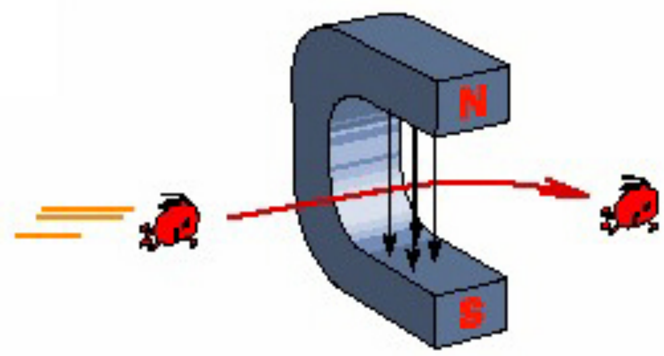
Used in medicine for electrons up to few MeV



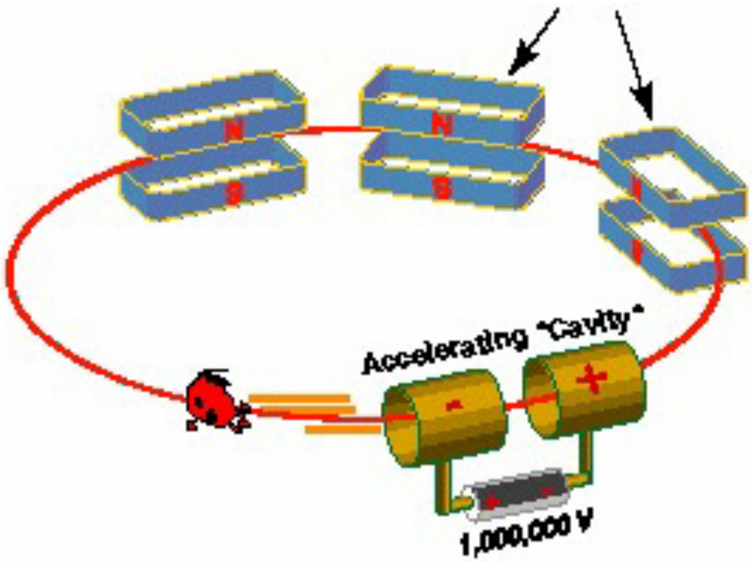
Accelerators: working principle



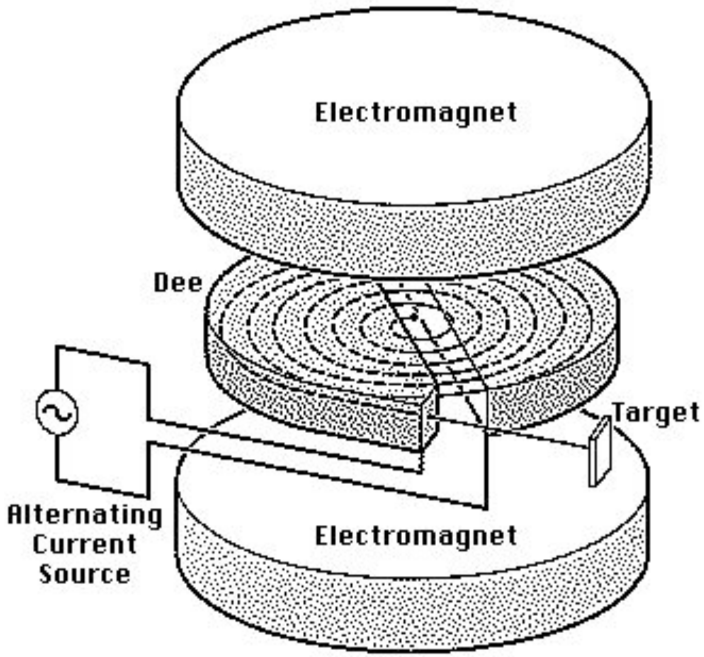
Accelration: electric field



Bending: magnetic field

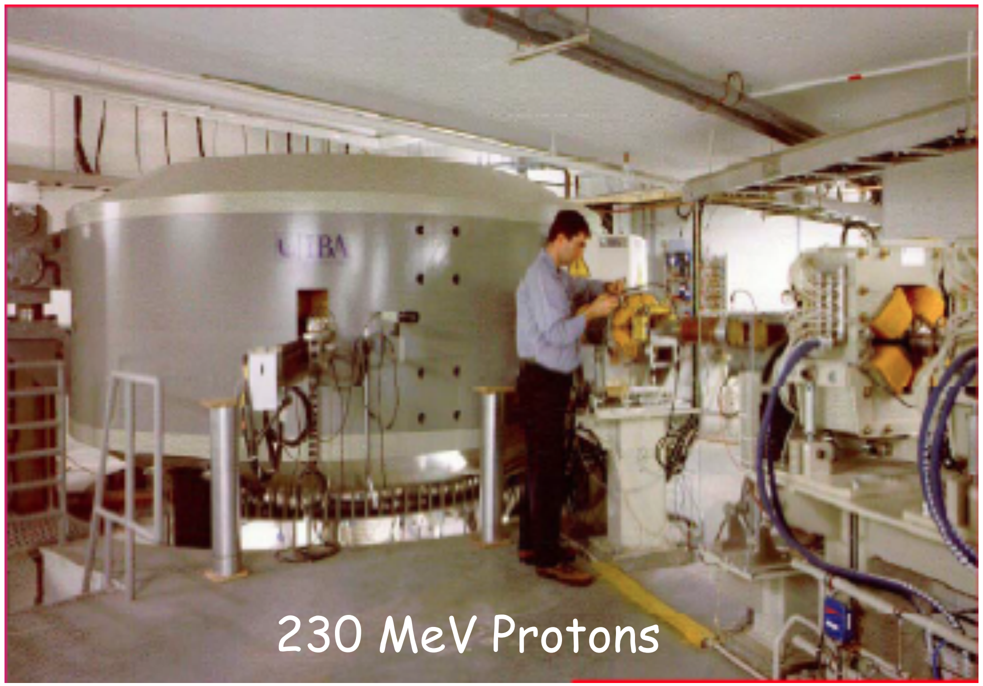


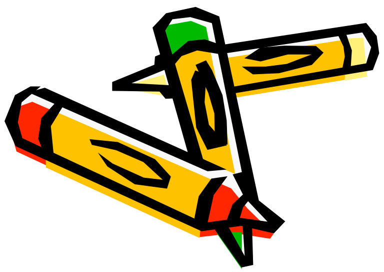
Accelerators: CYCLOTRON



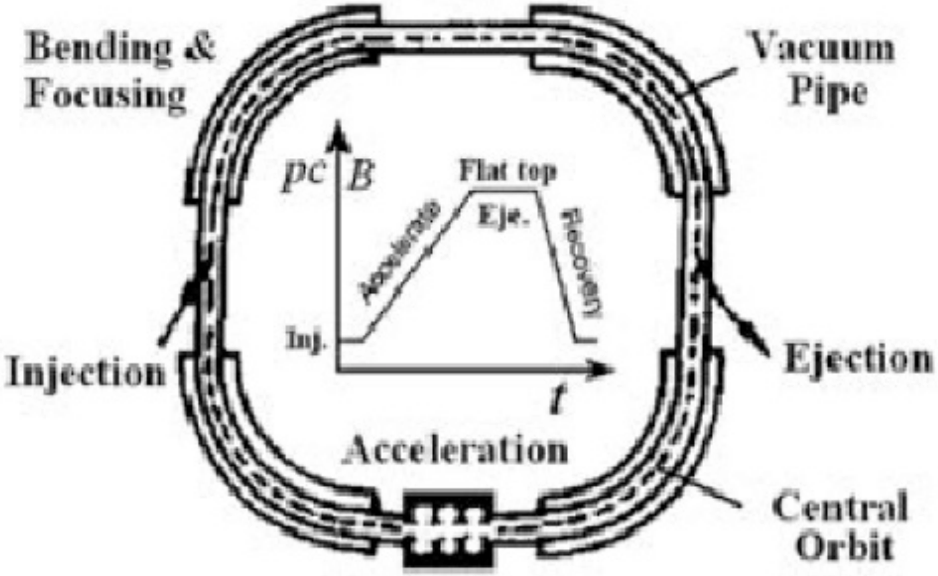
Used to accelerate protons/ions

- 10-30 MeV for radio-isotope production
- Up to 200 MeV for radio-therapy

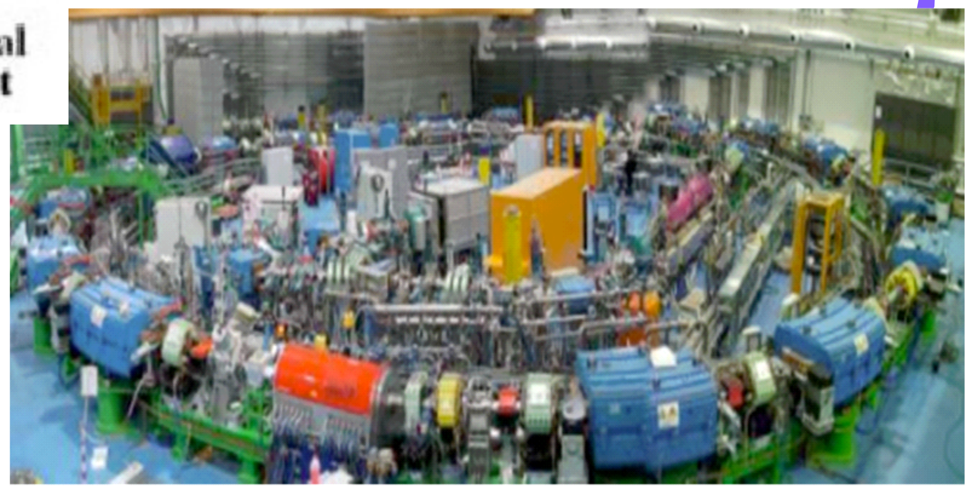




Accelerators: syncrotrons



Accelerate protons/carbons for therapy up to 4800 MeV



Medical accelerators

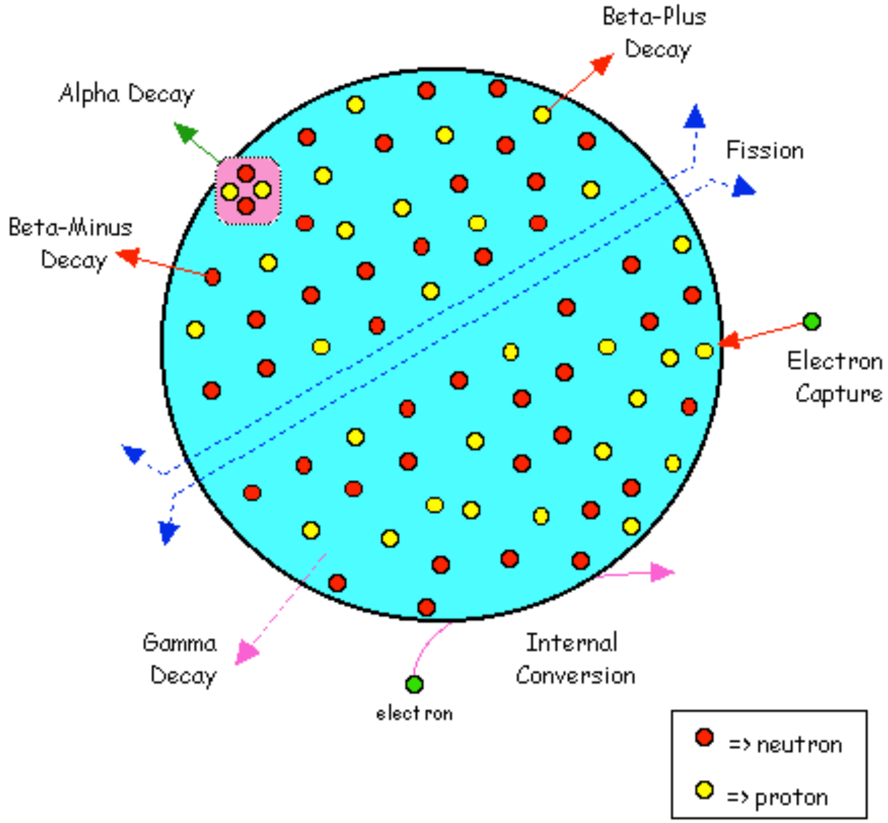
CATEGORY OF ACCELERATORS	NUMBER IN USE (*)	
High Energy acc. (E >1GeV)	~120	
Synchrotron radiation sources	>100	
Medical radioisotope production	~200	
Radiotherapy accelerators	> 7500	9000
Research acc. included biomedical research	~1000	
Acc. for industrial processing and research	~1500	
Ion implanters, surface modification	>7000	
TOTAL	> 17500	

(*) W. Maciszewski and W. Scharf: Int. J. of Radiation Oncology, 2004

Radio-isotopes

Unstable nuclei that decay with strong interactions

Produced:
- by strong reactions (bombardment of stable nuclei with protons)
- as remnants from reactors



Diagnostics and Nuclear Medicine

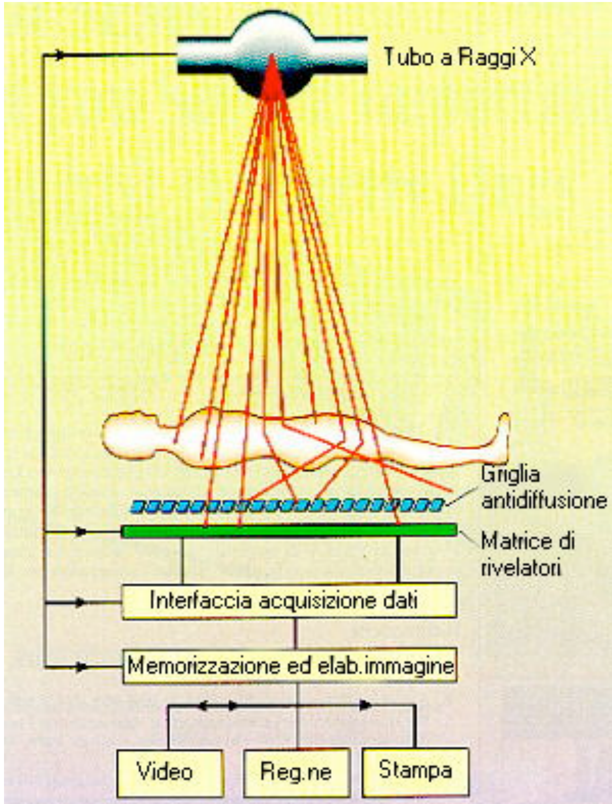
Diagnostics (radiography, SPECT, PET,...)
Molecular radiotherapy
Radio-guided surgery

Diagnostics

- Two major categories:
  - Morphologic: sensitive only to densities
    - Radiography
    - TAC
    - ultrasound, …
  - Functional: sensitive to organ functionalities
    - PET
    - SPECT
    - …

Diagnostics: radiography

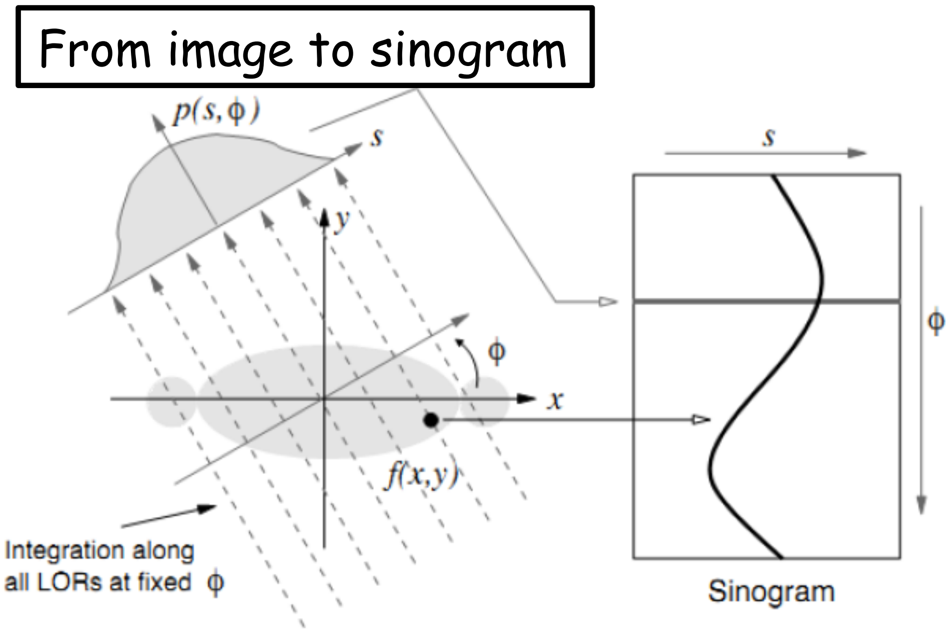
- X-rays produced with a cathodic tube by Bremsstrahlung
- Interaction between matter and patient
- X-ray detection

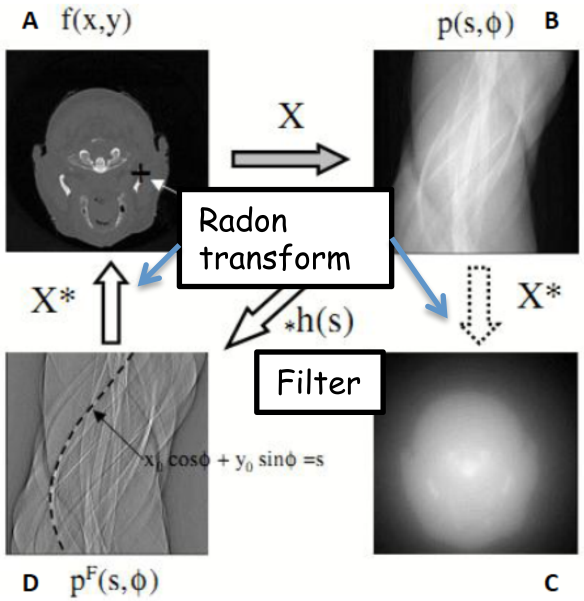


X-rays

Diagnostics: Tomography

- Generic mathematical tool from 1D → 2D
- CT with X-rays is most renown



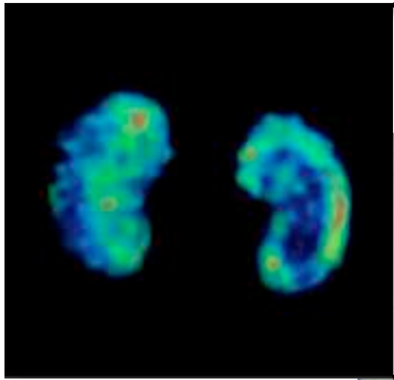


Radio-nuclides for imaging

- Administer, to patient (either systemically or locally) a drug which:
  - the tumor/organ of interest takes up significantly more than the rest.
  - is linked to a radio-nuclide that emits particles via nuclear decay
- Wait for the drug to diffuse
- Measure the emitted radiation and obtain information

Diagnostics: SPECT

Single Photon Emission Computerized Tomography

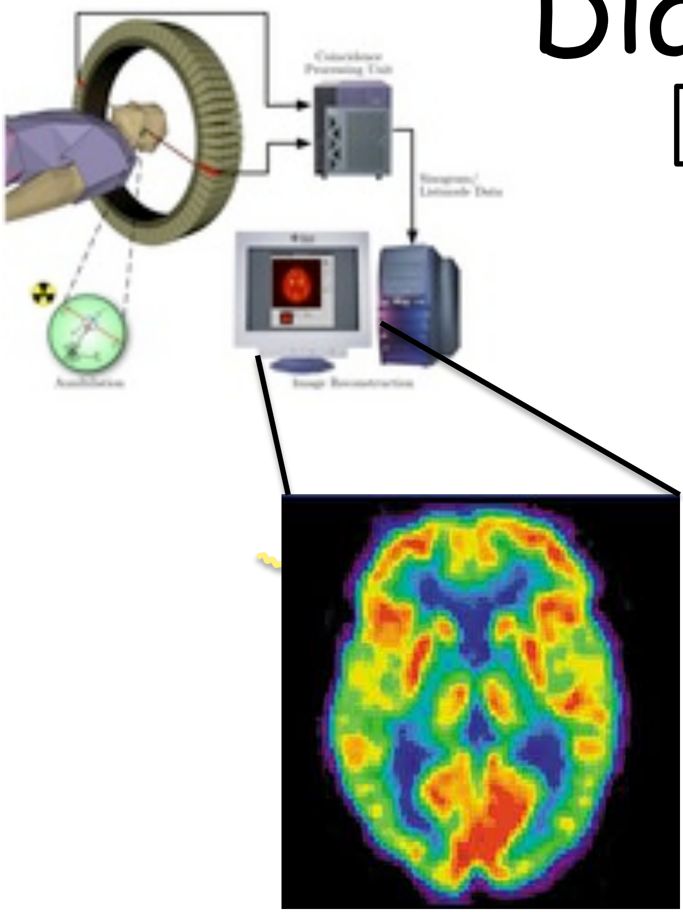


- Inject radionuclide (typically ^{99}Tc but also ^{131}I)
- Decays with single photon
- Detection ~50cm from source with anger camera

Gamma decays

Diagnostics: PET

Positron Emission Tomography



- Inject radionuclide (^{18}F in FDG, FET, 11C in methionine, choline)
- β+ decay
- Detect the two gammas in coincidence outside patient

Beta+ decays

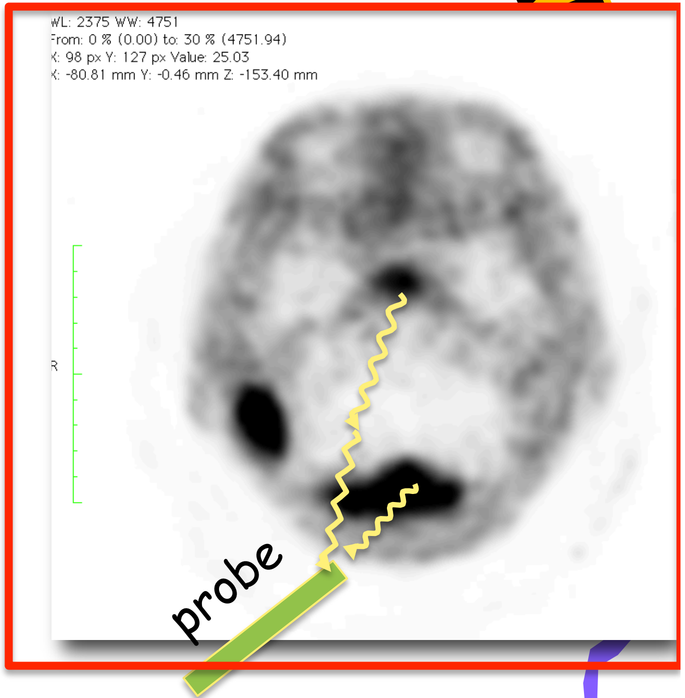
Radio-guided surgery

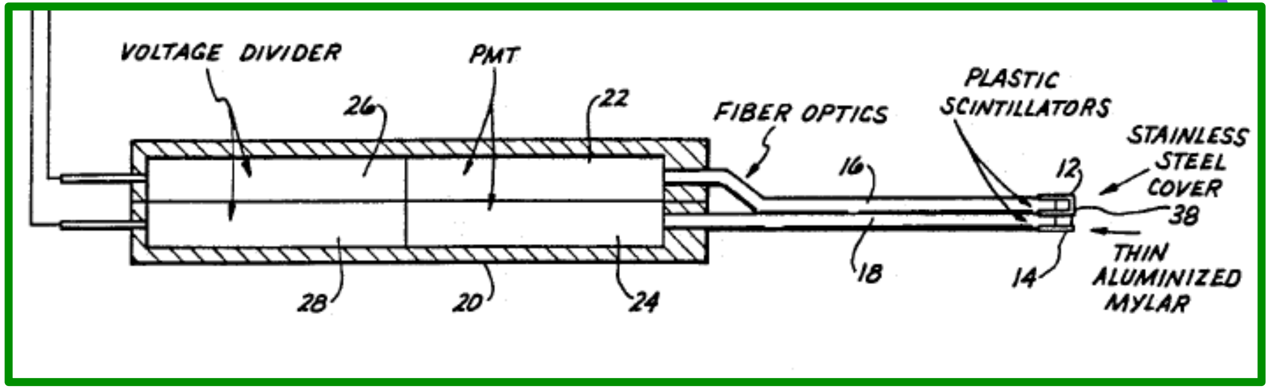
- Administer, before operation to patient (either systemically or locally) a drug which:
  - the tumor takes up significantly more than the healthy tissue.
  - is linked to a radio-nuclide that emits particles via nuclear decay
- Wait for the drug to diffuse to the margins of the tumor
- Start operation
  - Remove the bulk of the tumor
  - Verify with a probe that detects the emitted particles the presence of:
    - Residuals
    - Infected lymph nodes

Radioguided surgery

Three approaches

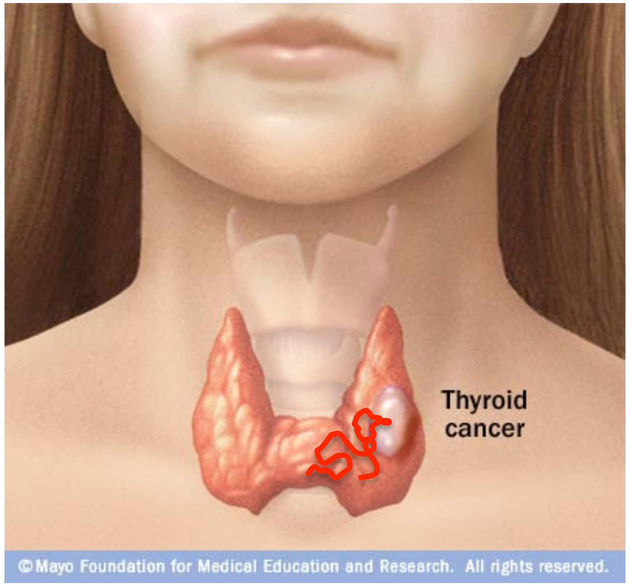
- Gamma: well established, e.g. sentinel lymph-node
- Beta+: based on the dual probe approach
- Beta-: future fronteer





radiomethabolic/ Brachitherapy

- Inject/ position radionuclide (e.g. 131I)
- Beta- decays
- Electrons release energy in tumor locally



Beta- decays

Physics Building Blocks of Diagnostics

- Nuclear decays
- Production of radiation source:
  - X rays
  - Radio-nuclides → nuclear reactions/ accelerators
- Dosimetry
- Detectors for photons and electrons

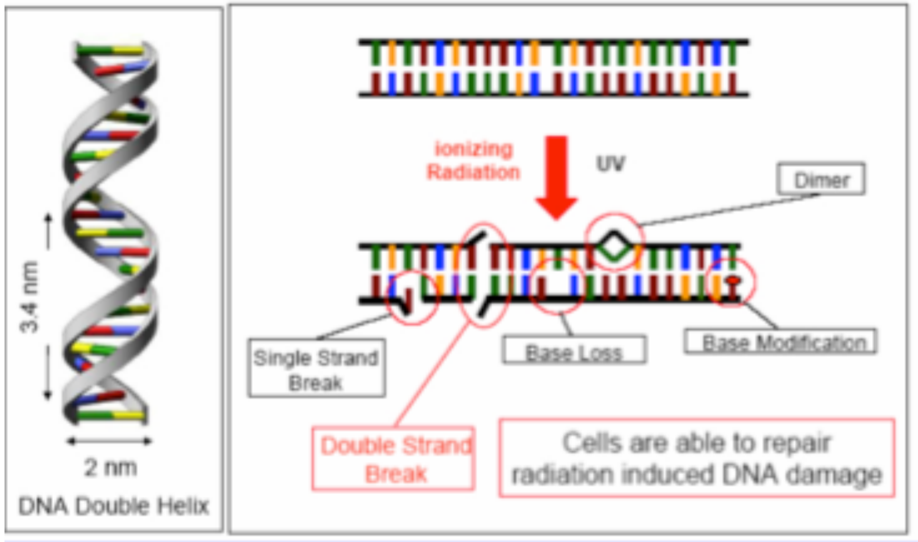
Radiotherapy

From conventional to Hadrotherapy

Radiotherapy

Goal:

- Deliver energy on tumor cells in order to break them in an irreparable way

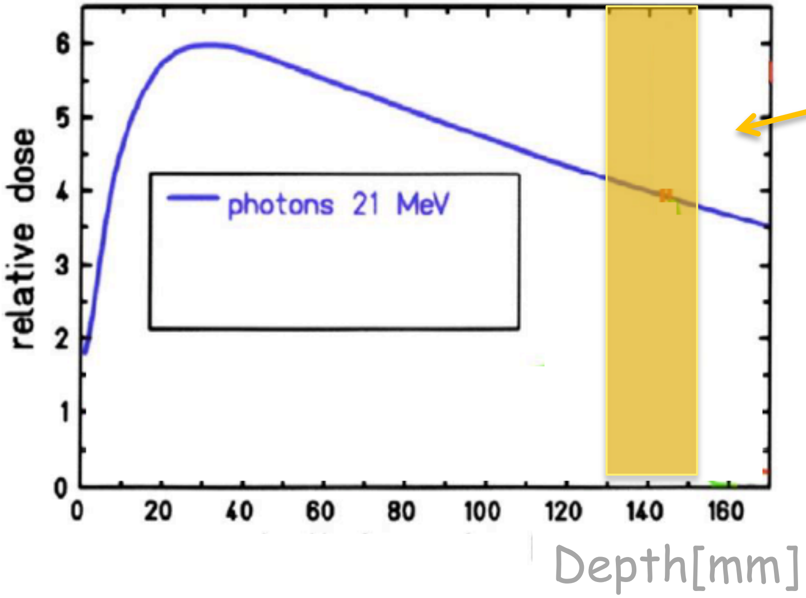


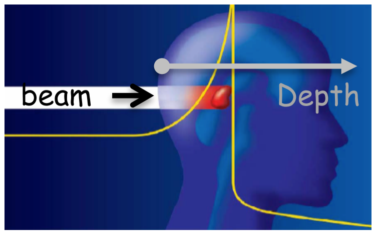
Large dE/dx
➔ DNA breaks irreparably

Moderate dE/dX
➔ chemical reaction due to free radicals

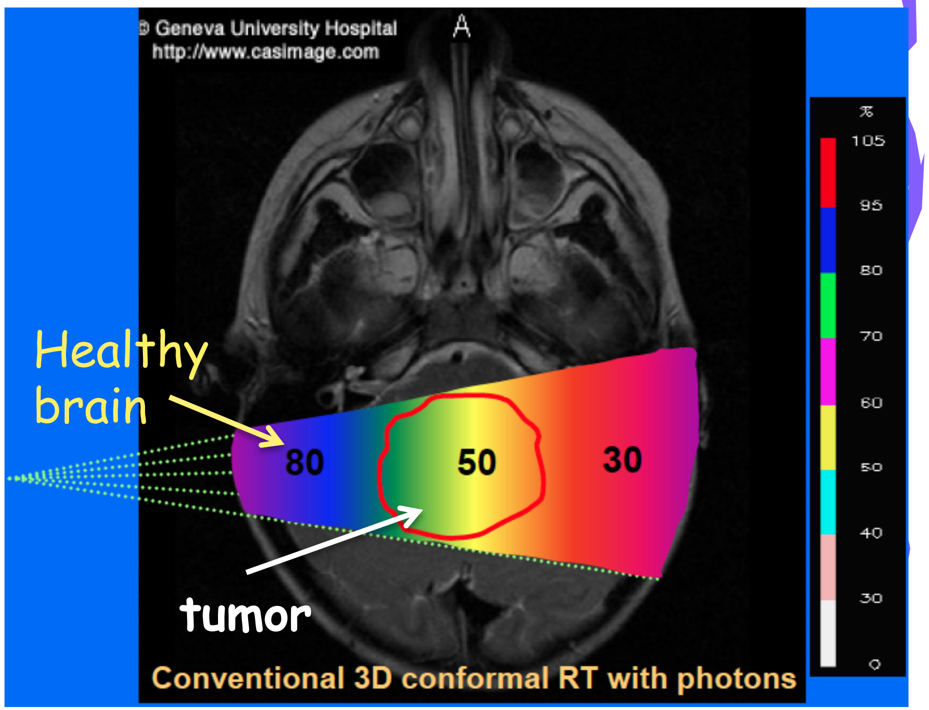
Conventional radiotherapy

Photon beams on patient



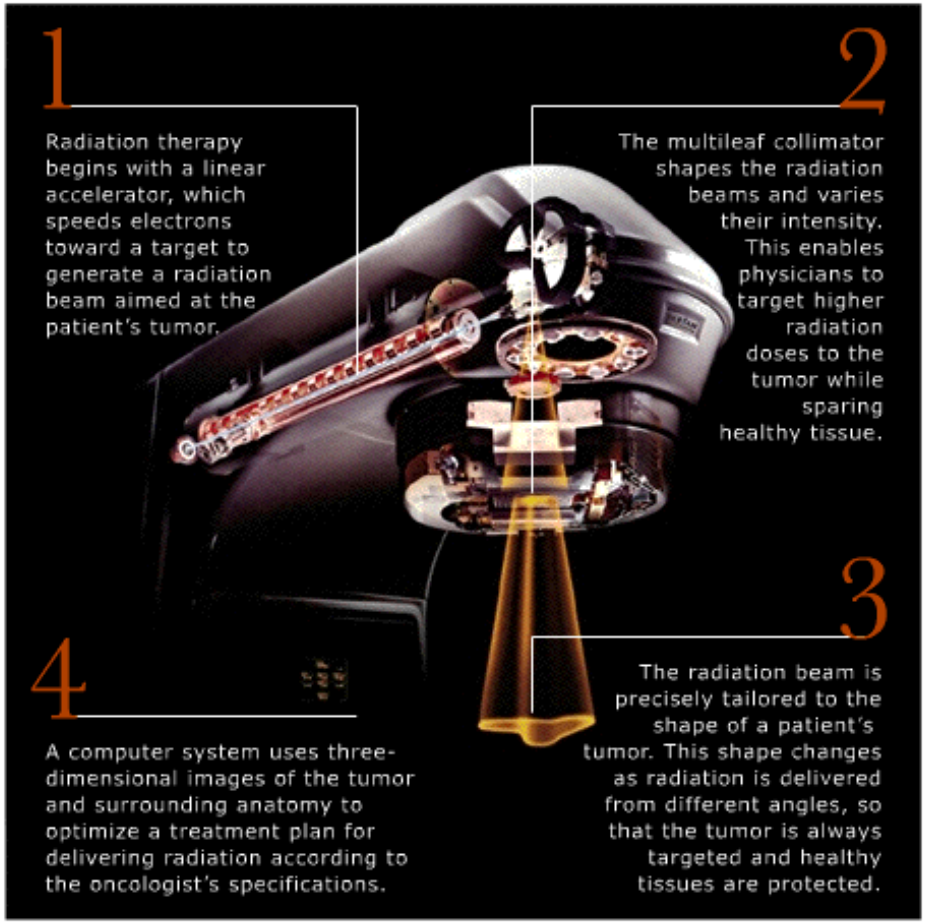


Large release of energy outside tumor



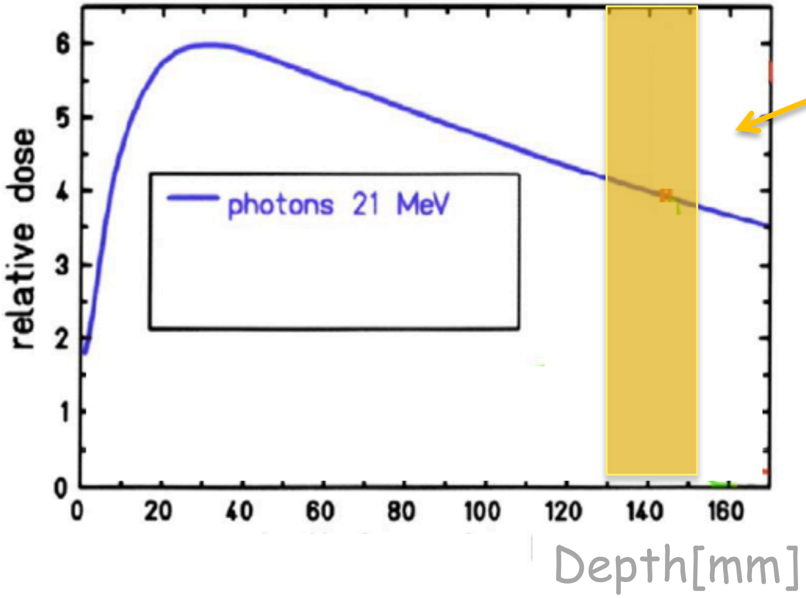
Radiotherapy LINAC

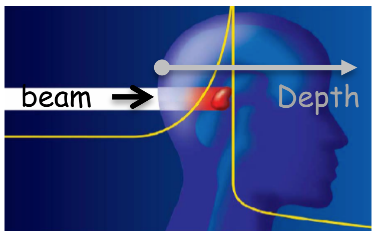
How a Linac Works



Conventional radiotherapy

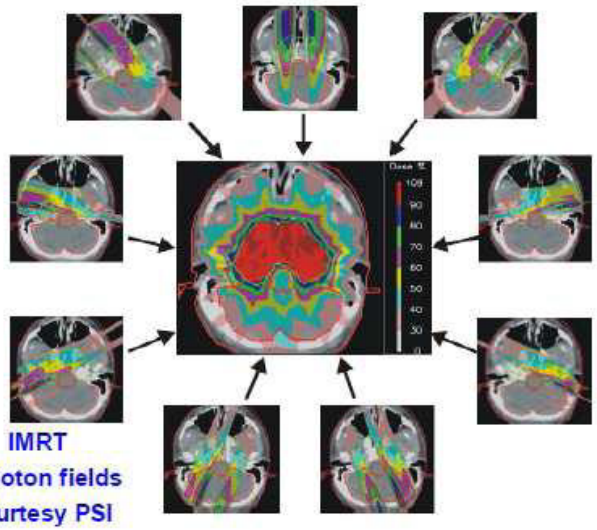
Photon beams on patient





Large release of energy outside tumor

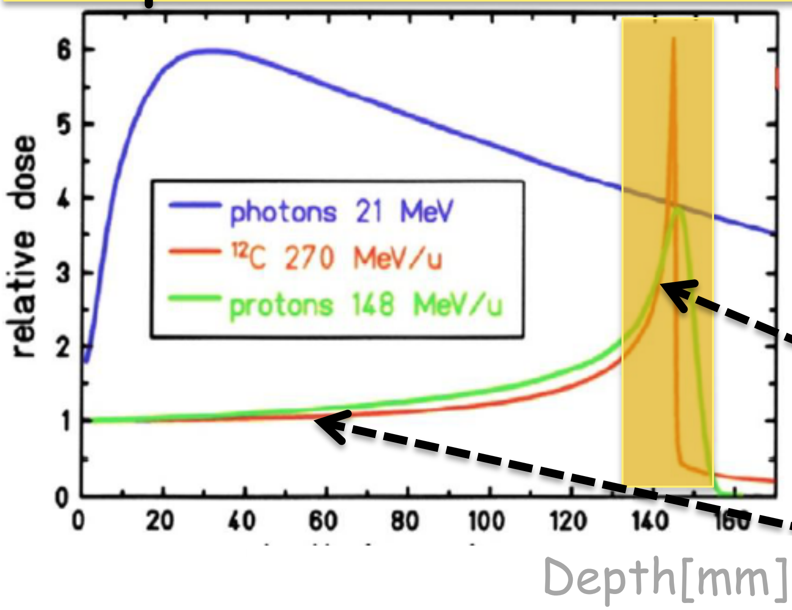
- Multiple beams each of smaller energy (IMRT)

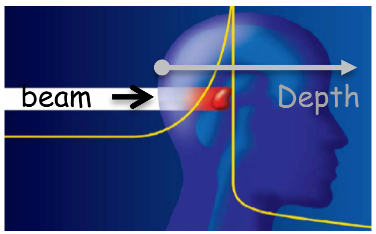


IMRT
9 photon fields
Courtesy PSI

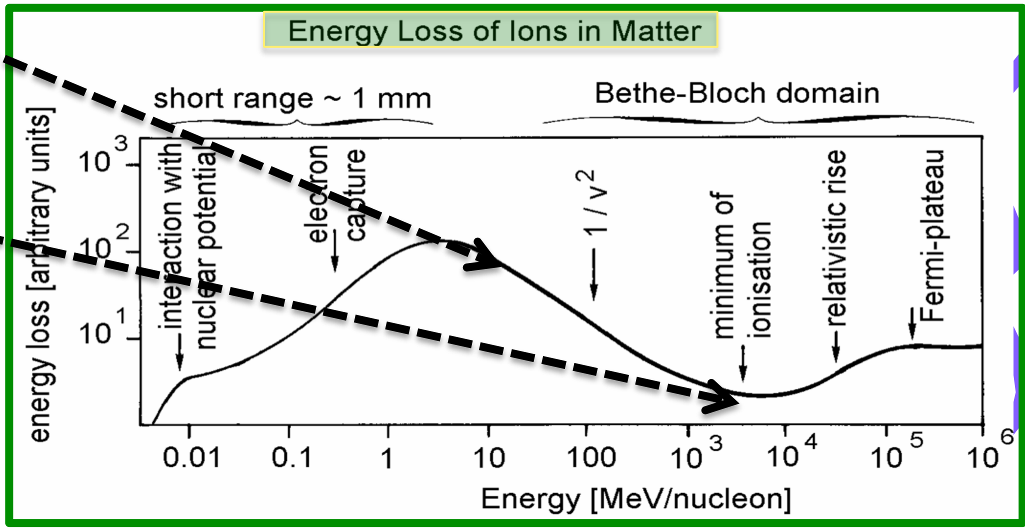
Hadrontherapy

Proton/ion beams on patient



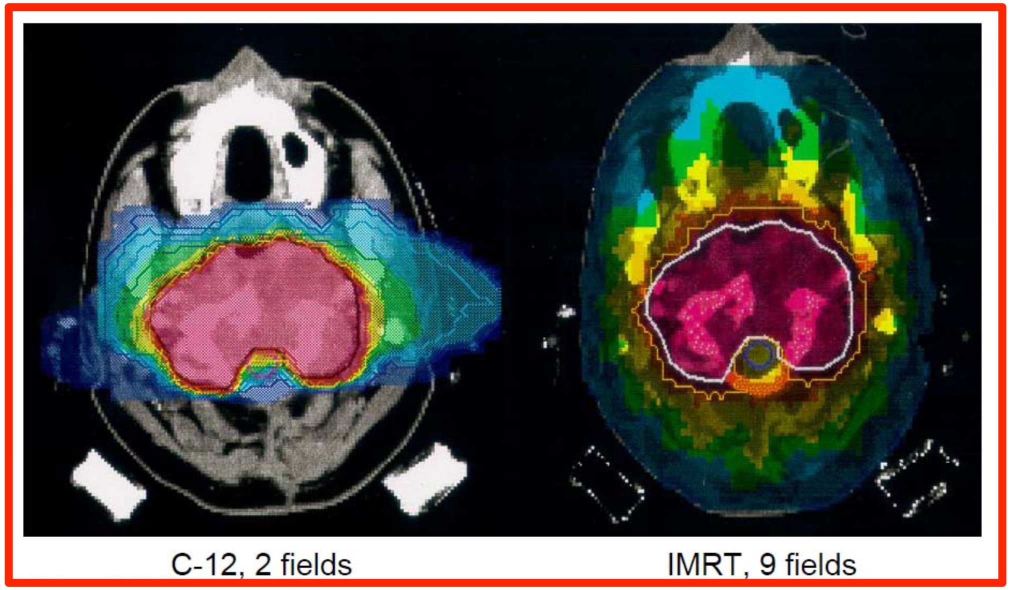


Concentrate release of energy inside tumor due to release of energy in ionization.

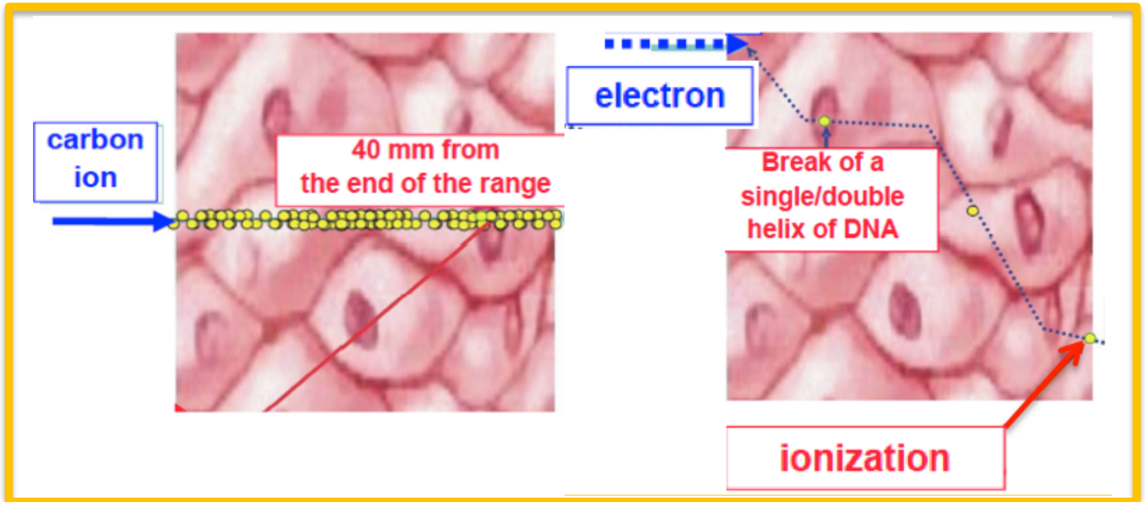


Comparison ^{12}C vs IMRT

Better confinement of energy release

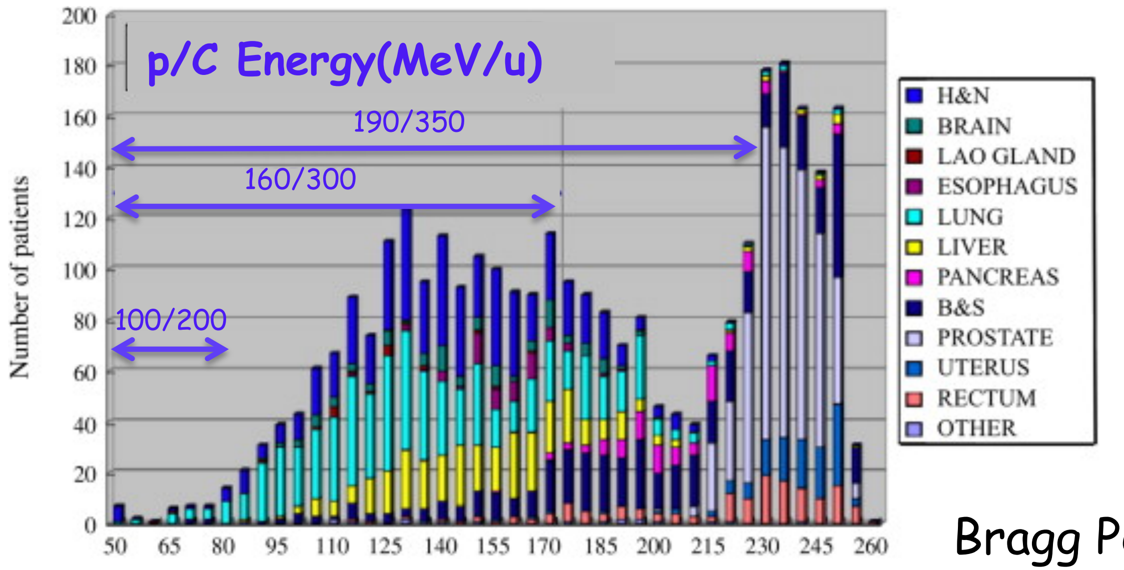


More effectiveness in killing cells



Accelerators

Required proton/
Carbon energy



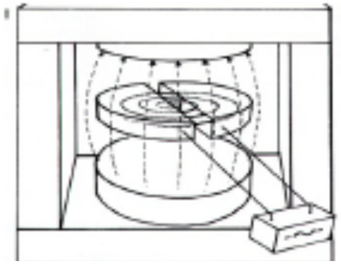
Bragg Peak
depth (mm)

Proton Kinetic Energy between 100-250 MeV
Carbon Kinetic Energy between 200-400 MeV/u

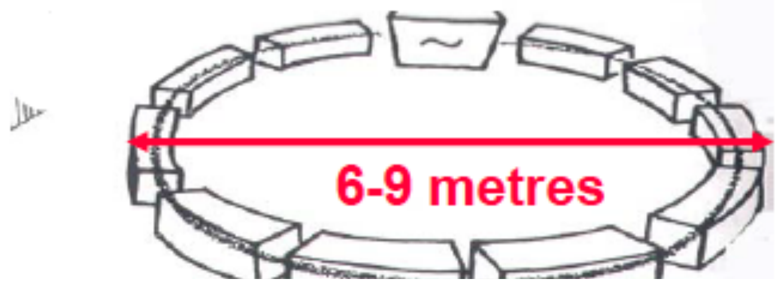
Accelerators for hadrotherapy

therapy with protons (~ 200 MeV)

CYCLOTRONS (Normal or SC)

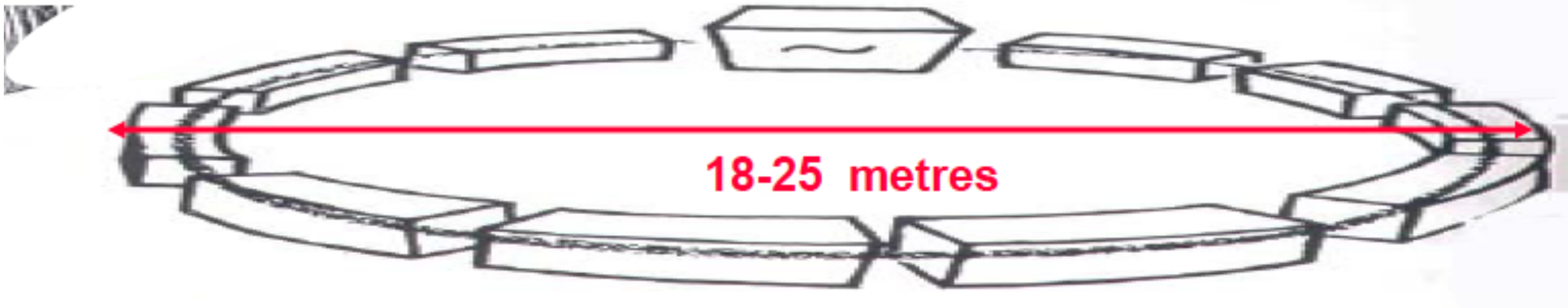


SYNCHROTRONS

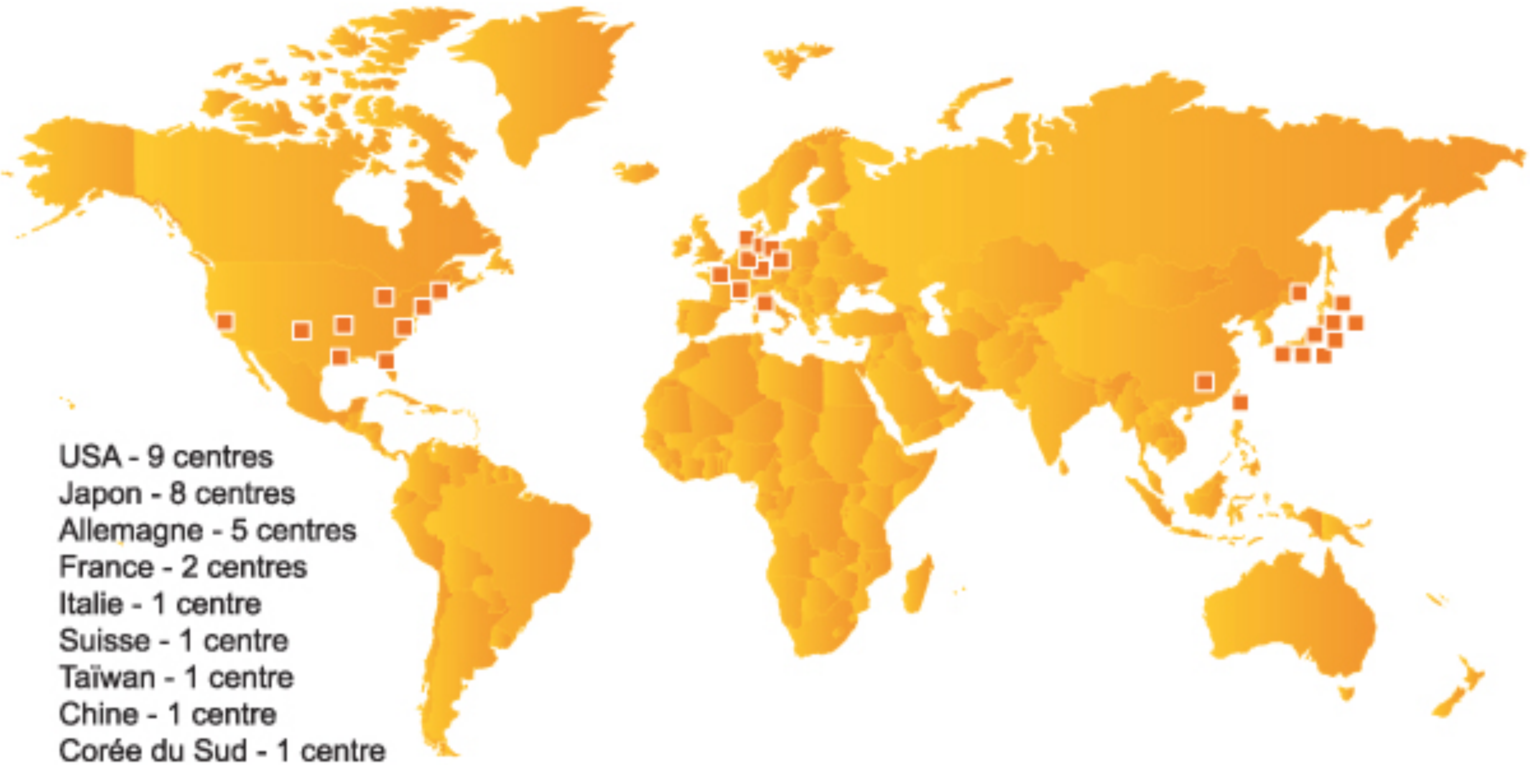


therapy with carbon ions (~ 4800 MeV)

SYNCHROTRONS

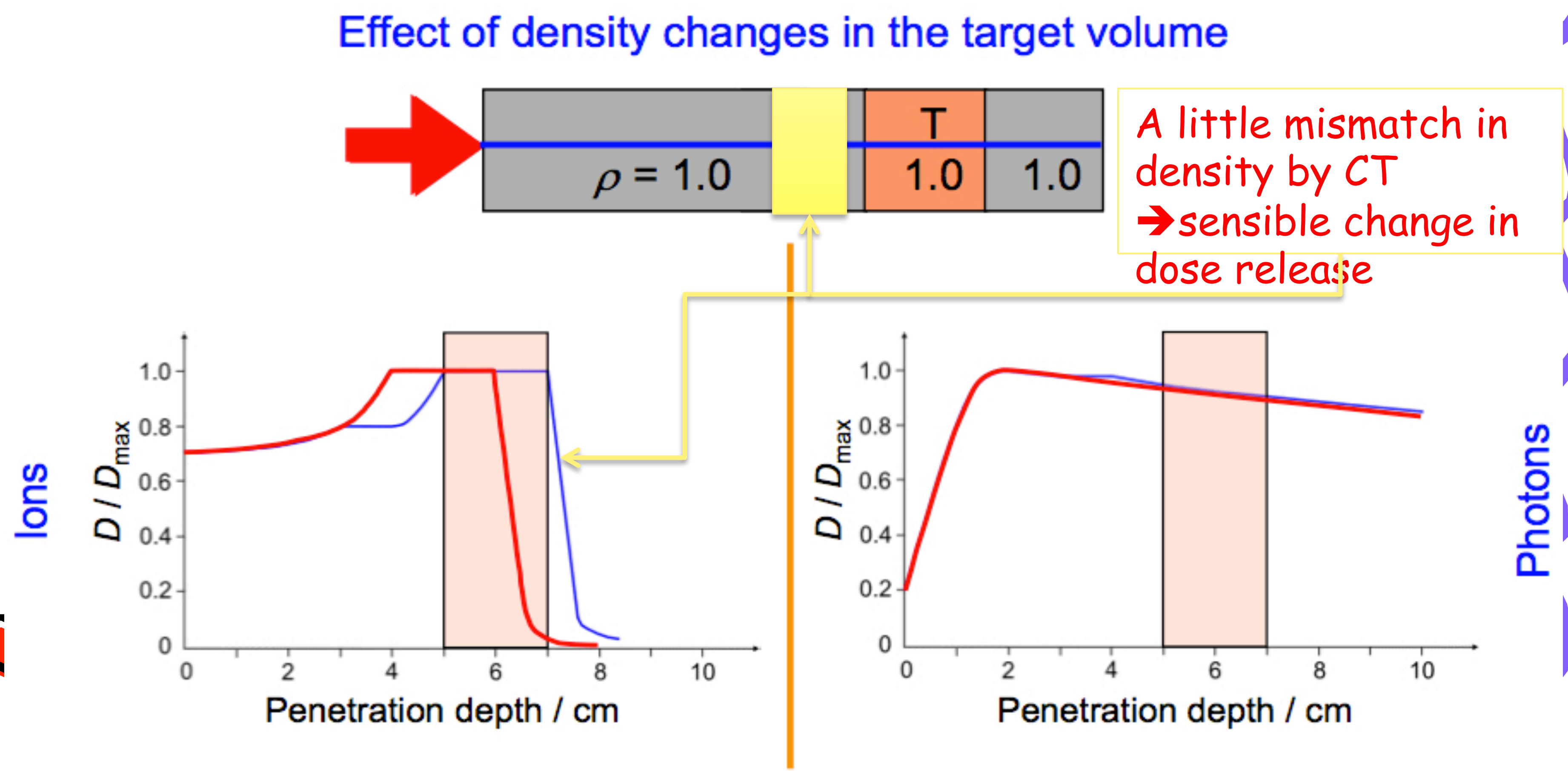


Present of hadrotherapy



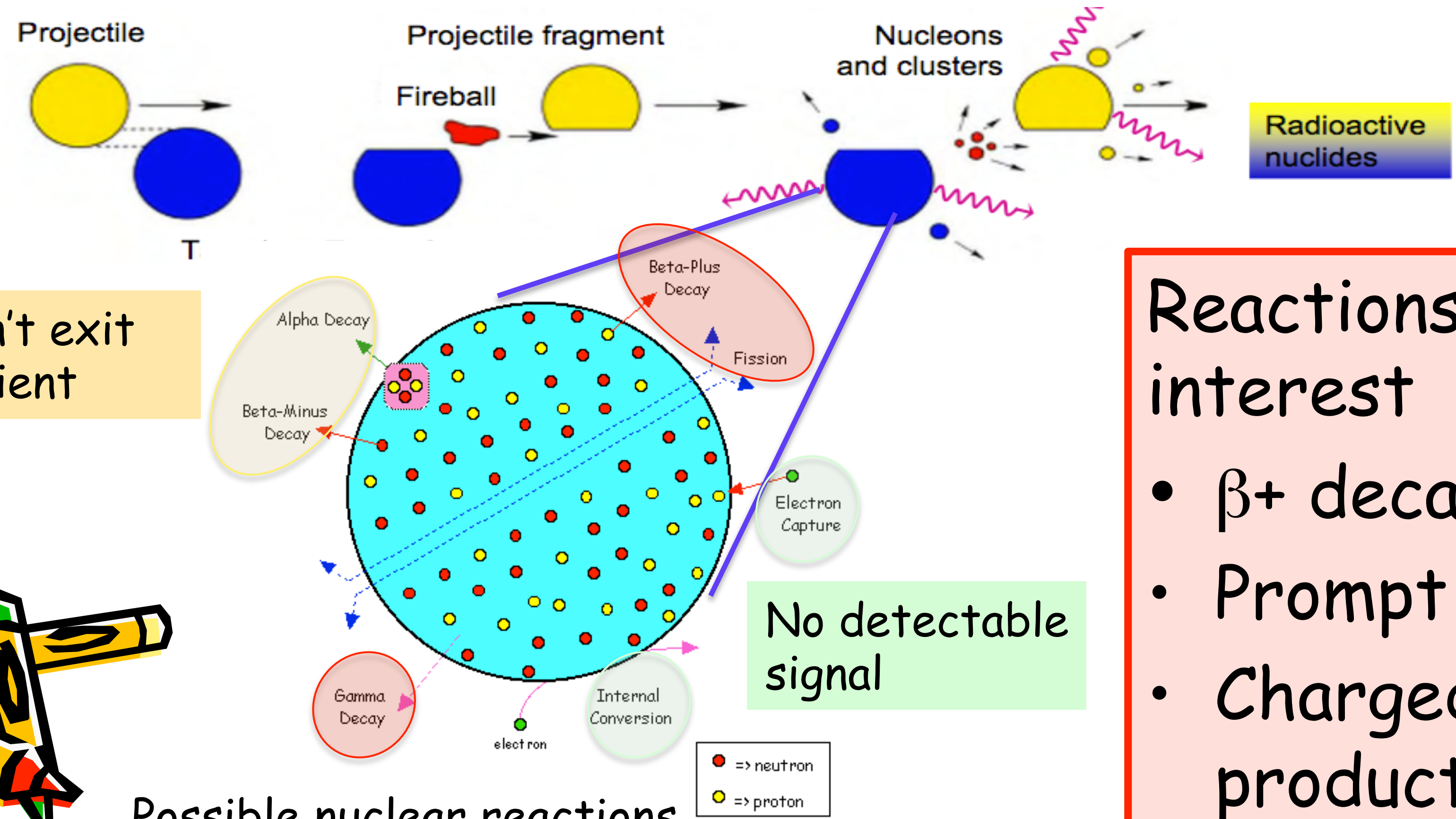
HT:Monitoring the dose

- Why is so crucial to monitor the dose in hadrontherapy ? Is like firing with machine-gun or using a precision rifle..



Measuring the dose

Based on nuclear reactions between the projectile and the patient



Don't exit patient

No detectable signal

Possible nuclear reactions

Reactions of interest

- β+ decays
- Prompt γ
- Charged products

Physics in Medicine

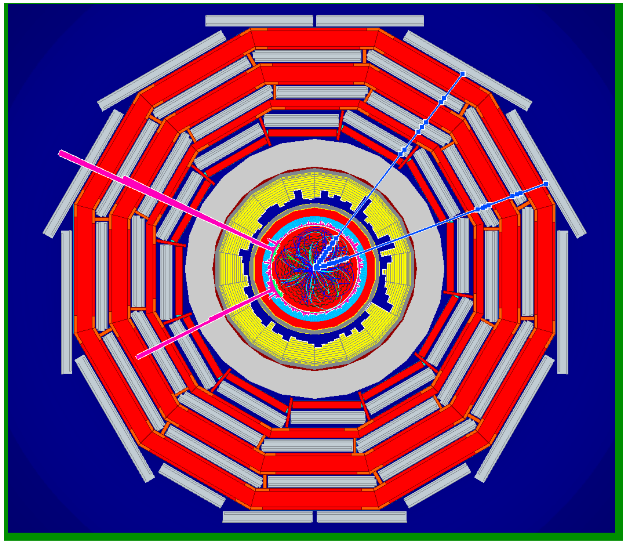
Nuclear decays

Radio Isotopes

Particle-matter interactions

Radiation detection

Particle accelerators



PHYSICS IS BEAUTIFUL …

… AND USEFUL

(U. Amaldi)