SMALL PARTICLE ACCELERATORS

and their

APPLICATIONS IN MEDICINE AND INDUSTRY

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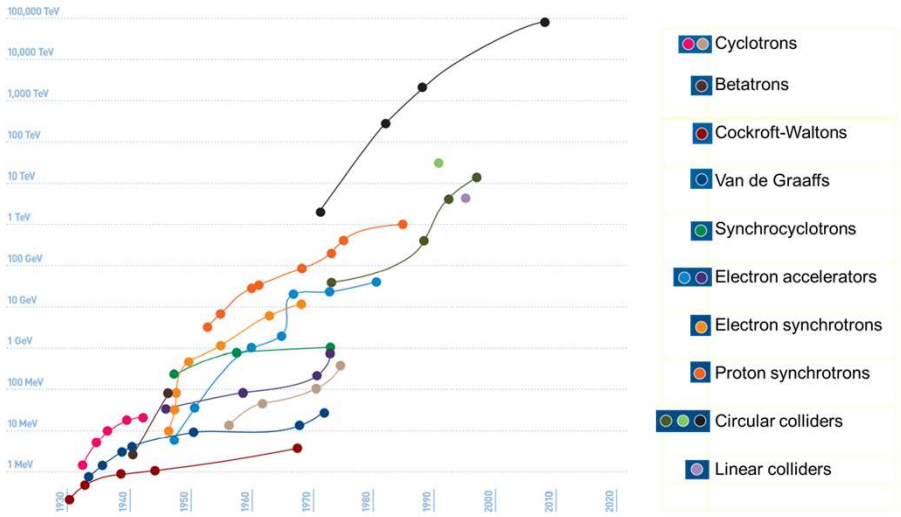
GHENT UNIVERSITY

iFAST Innovation Fostering in Accelerator Science and Technology

Accelerators in High-Energy Physics

Livingston plot

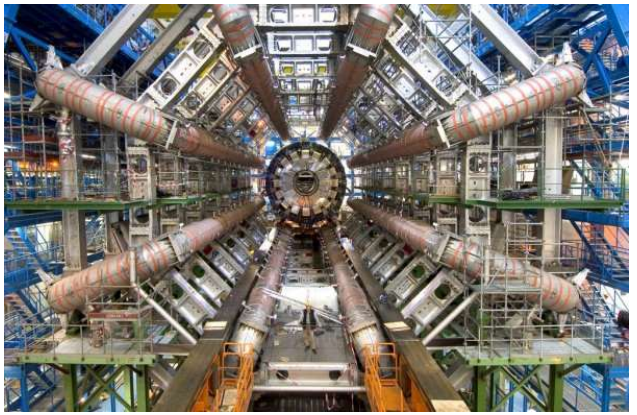


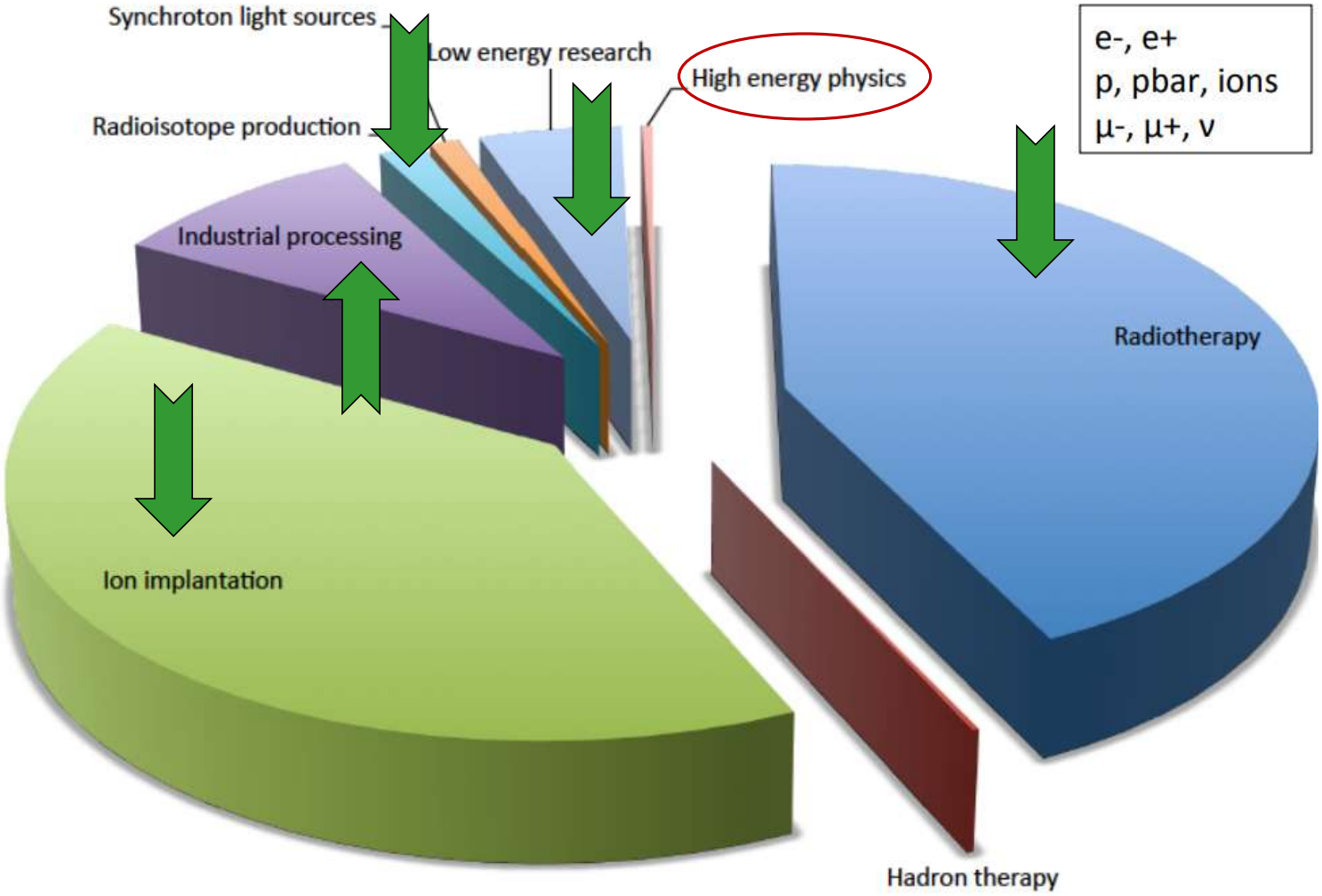
Energy reach of the highest-energy particle accelerators ever built. The energy of particle colliders is plotted in terms of the energy that the particles would need if colliding with a proton at rest. Using these units, the energy of at the Large Hadron Collider corresponds to the energy of nearly 100,000 TeV.

Accelerators:

- world's **largest and most complex** scientific instruments
- **dimensions** in the km-range
- big institutes with **highly experienced staff**
- budgets affordable only on an **international scale**
- usually machines are **prototypes,** developed in-house

During the last 80 years **accelerators contributed to 25 Nobel prizes in Physics** shared by 42 scientists





~ 45,000 accelerators in operation all over the world (estimation in 2020)

All different accelerator types are **spin offs** of accelerators for nuclear and particle physics

~ 95% of all accelerators are small accelerators, energy < 50 MeV

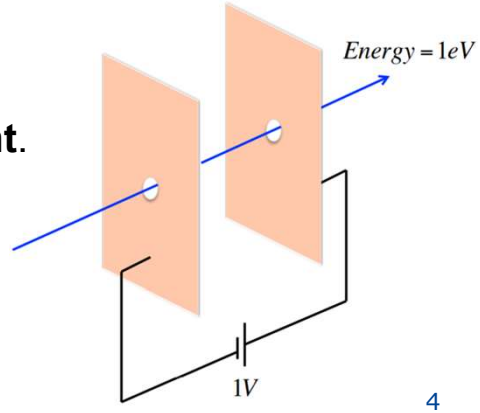
Small accelerators for

1. medicine
2. industry
3. analytical techniques (low-energy research)

Adapted to an industrial, medical or small laboratory environment:

- **fit easily into a production line or in a hospital room:** compact footprint and radiation shields.
- **simple in construction, operation and maintenance:** purpose-built and standardised.
- **competitive:** small crew, electrically-efficient, reliable, fail-safe autonomous running.
- **beam currents up to six decades higher**.
- beam **quality parameters** (momentum resolution, beam emittance) are **less important**.

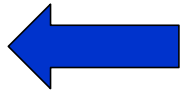
- low-energy accelerators < **50 MeV**



Outline

1. Introduction

2. Small accelerators for applications



3. Applications in medicine
   - radiotherapy
   - production of radioisotopes

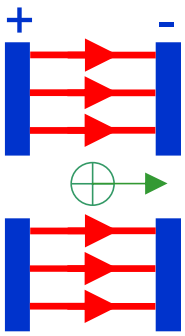
4. Applications in industry
   - radiation processing
   - ion beam applications

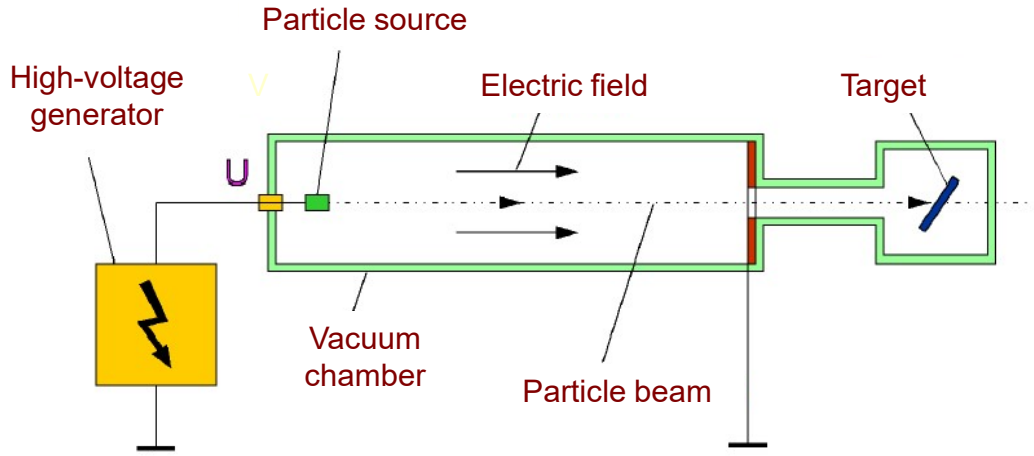
5. Analysis of physical, chemical or biological properties of materials
   - with photon or neutron beams
   - with ion beams

Which accelerator types are used for applications?

1. Electrostatic accelerators
2. Radiofrequency accelerators

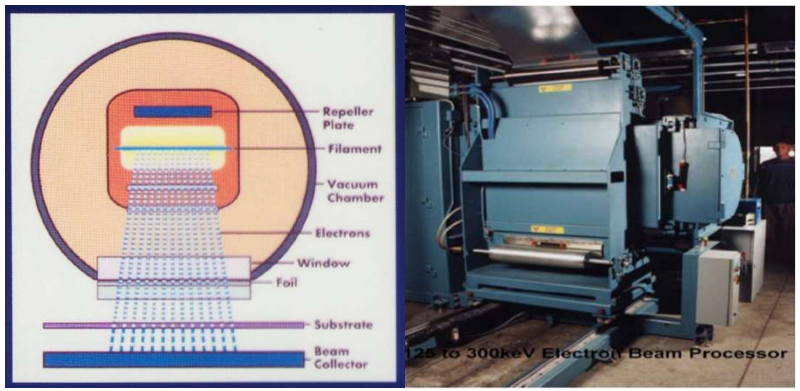
1. <u>Electrostatic accelerators</u>:
'one step' acceleration



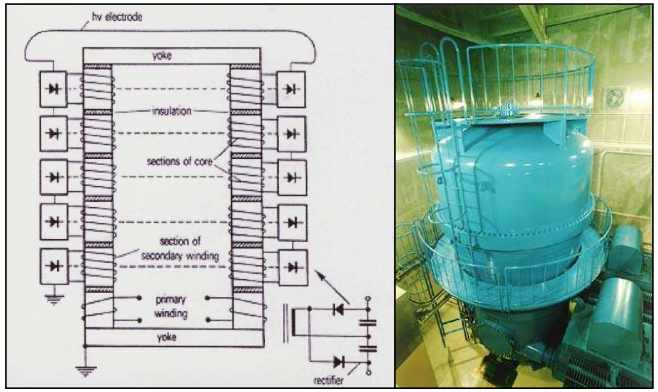


- electrons, protons, ions
- energy < 10 MeV
- high-power beams
- industrial applications

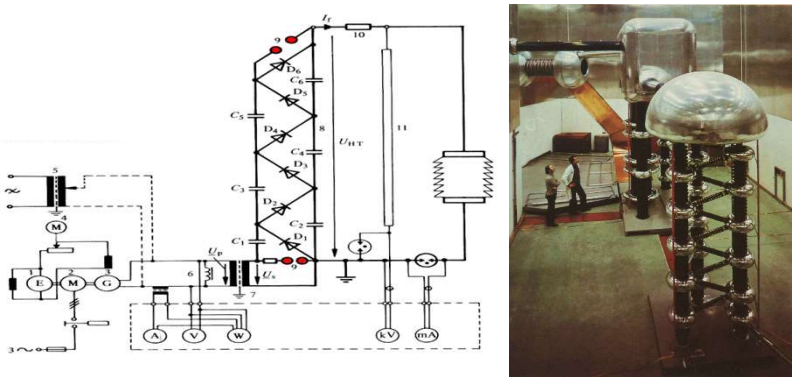
1. **Electrostatic accelerators**: broadbeam accelerators, or accelerators with scanning magnet



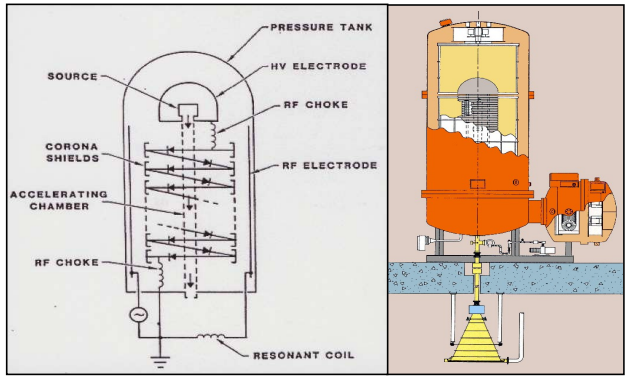
Electrocurtain accelerator



Insulated-core transformer



Cockroft-Walton accelerator



Dynamitron

- electrons, protons, ions
- energy < 5 MeV
- high-power beams
- radiation processing (e^-,X)
- ion implantation (ions)

Small accelerators for applications

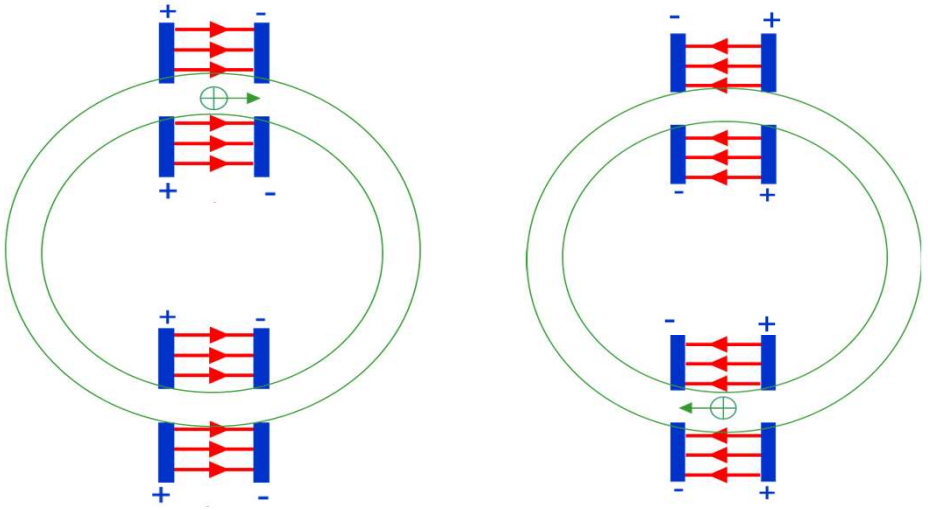
2. **Radiofrequency accelerators**:
repetitive acceleration with time-dependent electric fields (2 options)

LINEAR

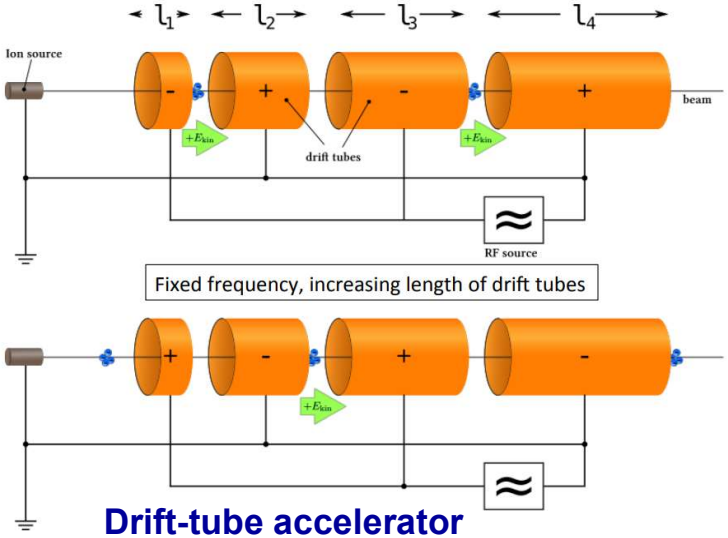
t = 0 t = T/2

Synchronism !

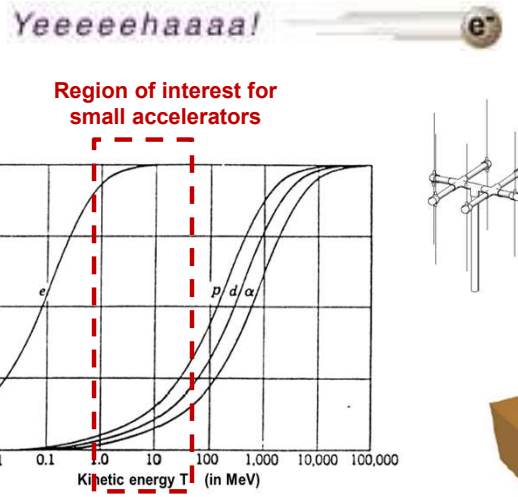
CIRCULAR

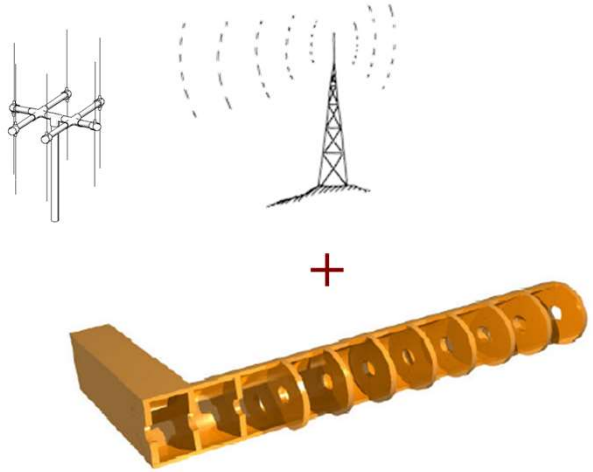


Linear accelerators

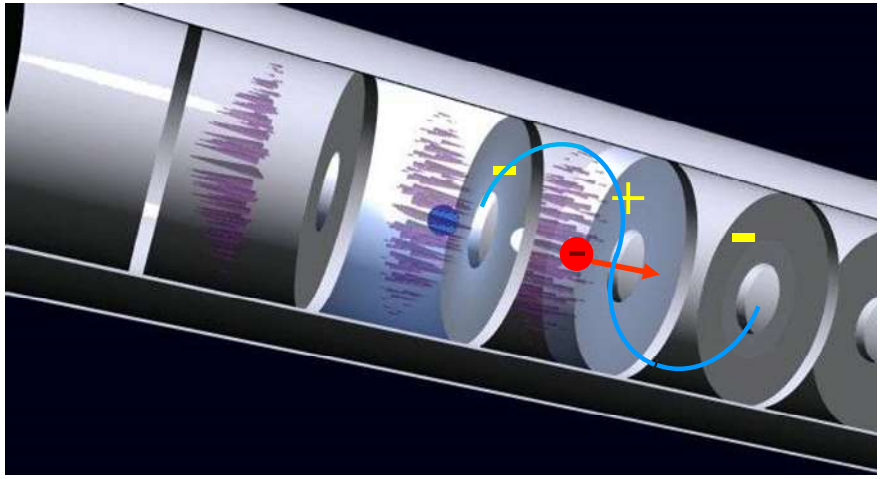


Drift-tube accelerator

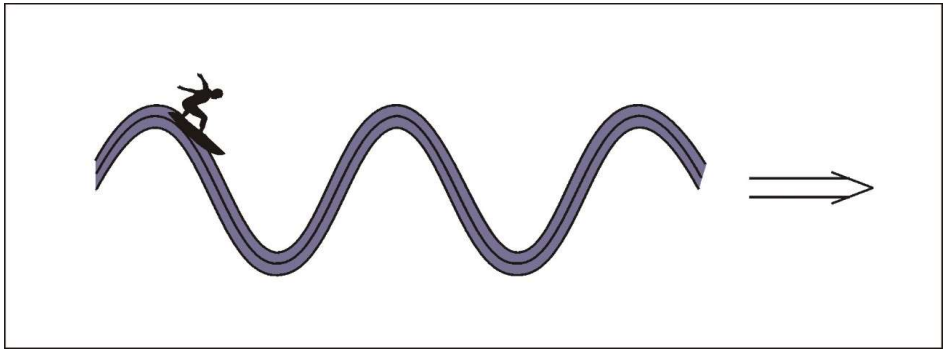




for e^- we need electric fields moving at speed of light



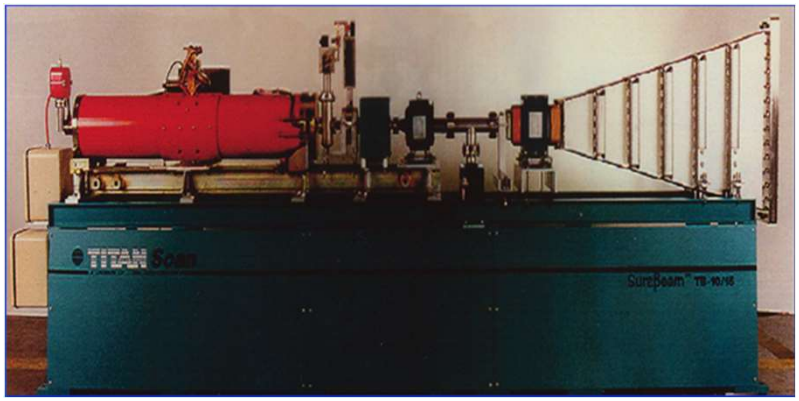
Travelling-wave accelerator or LINAC



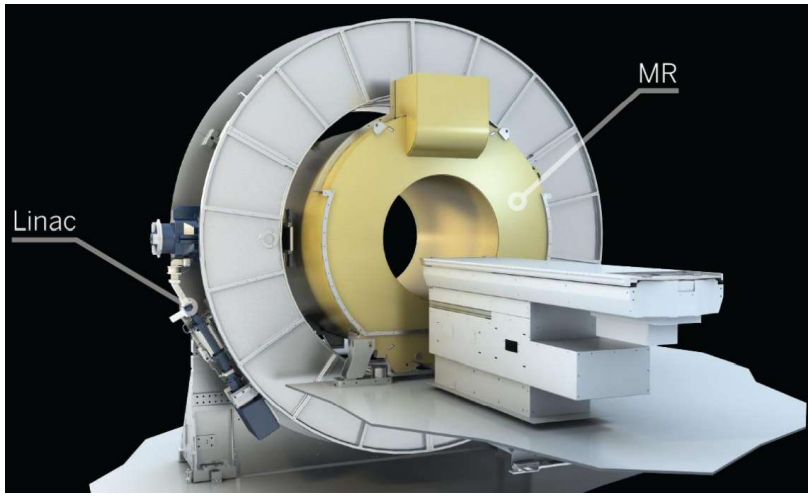
2. Linear radiofrequency accelerators:

- electrons & protons
- energy < 50 MeV
- radiotherapy (e^-, X)
- radiation processing (e^-, X)
- isotope production (p)

Electron LINAC for radiotherapy



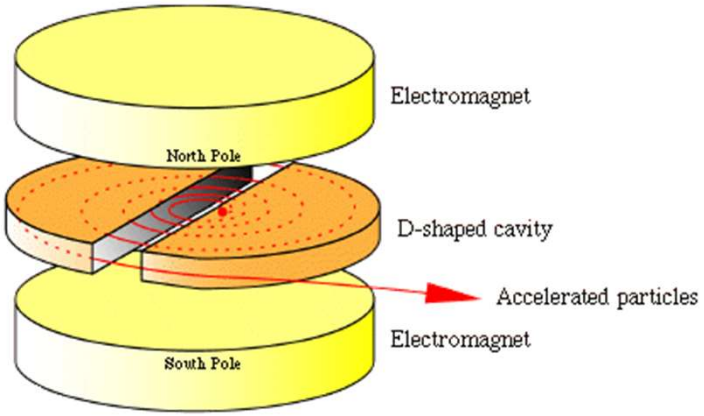
Electron LINAC for radiation processing



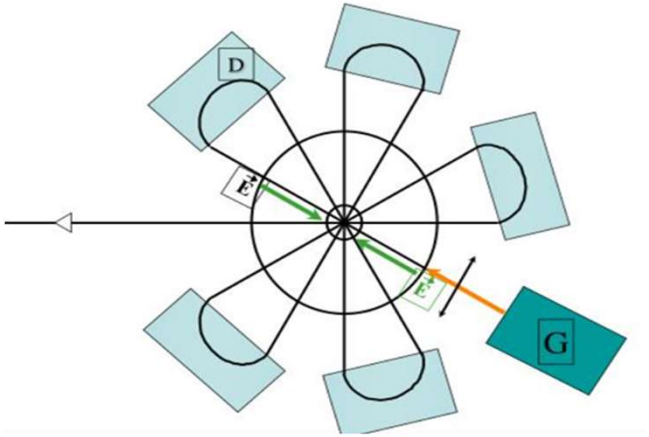
Radiotherapy electron LINAC within MRI

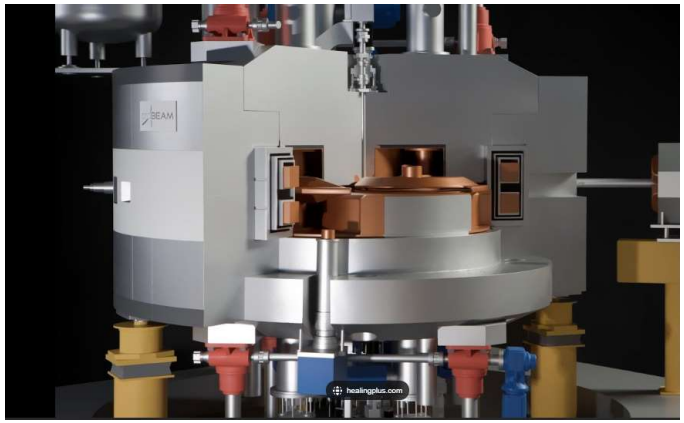
Proton drift-tube accelerator for neutron or isotope production

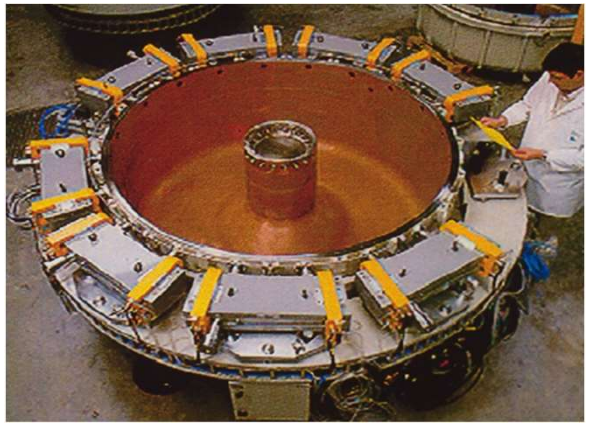
Circular accelerators



'folded drift-tube accelerator'



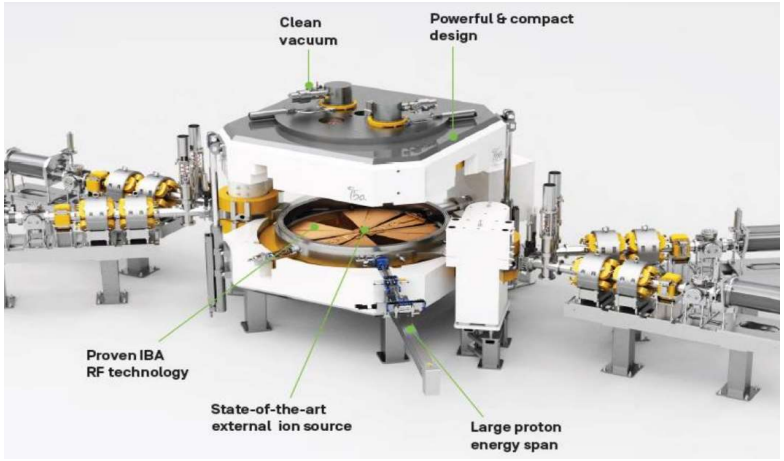




CYCLOTRON
protons, deuterons, alphas

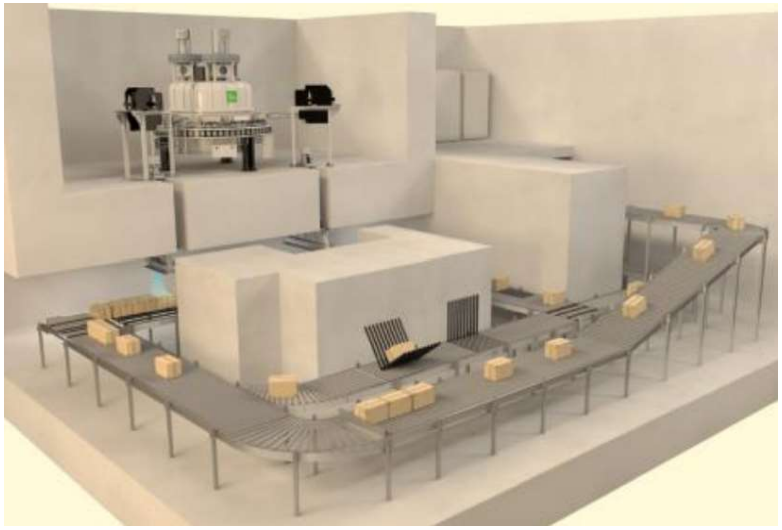
RHODOTRON
electrons

3. Circular radiofrequency accelerators:



CYCLOTRON for isotope production

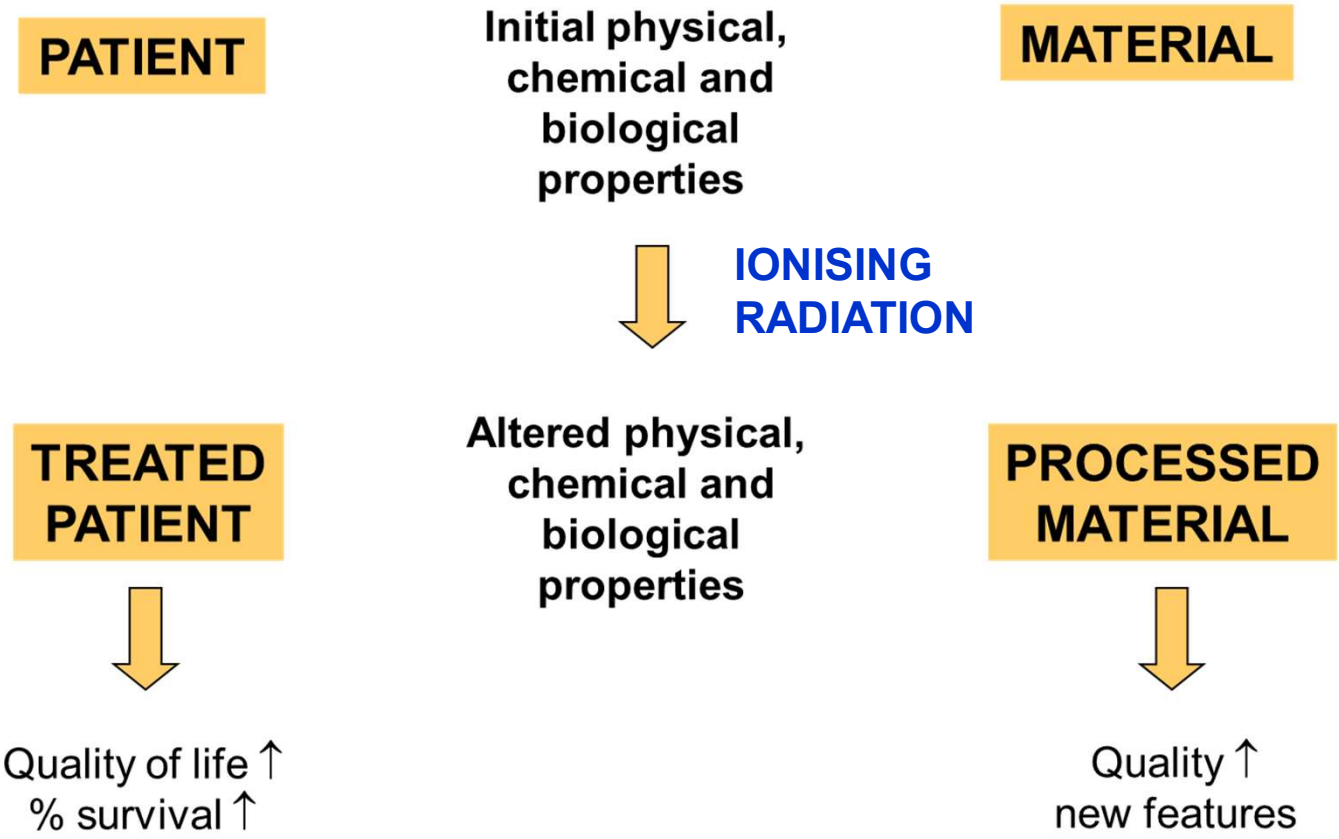
- protons, deuterons, alphas
- energy < 30 MeV
- high-power beams
- isotope production (p, d, α)



RHODOTRON radiation processing

- electrons
- energy < 10 MeV
- high-power beams
- radiation processing (e^-, X, up to 10 MeV)
- isotope production (X, up to 50 MeV)

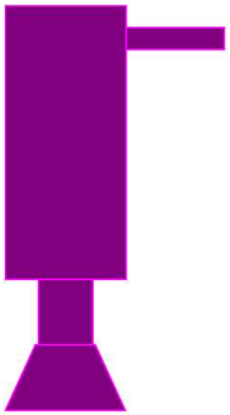
Small particle accelerators in medicine or industry



!! Minimum side-effects !!

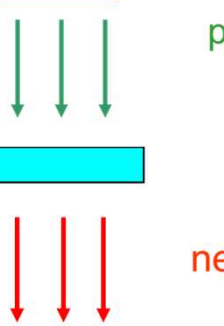
Small particle accelerators in medicine or industry

primary beams

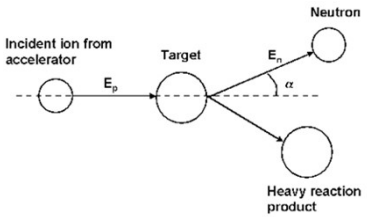


protons
ions

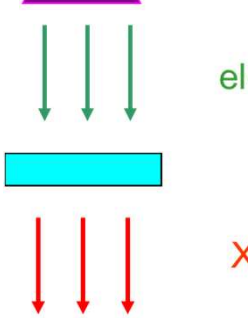
secondary beams



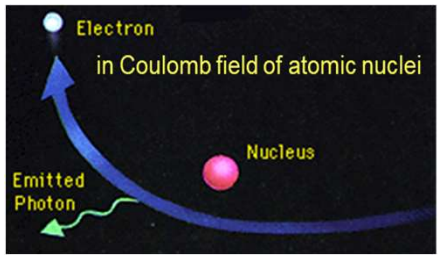
neutrons



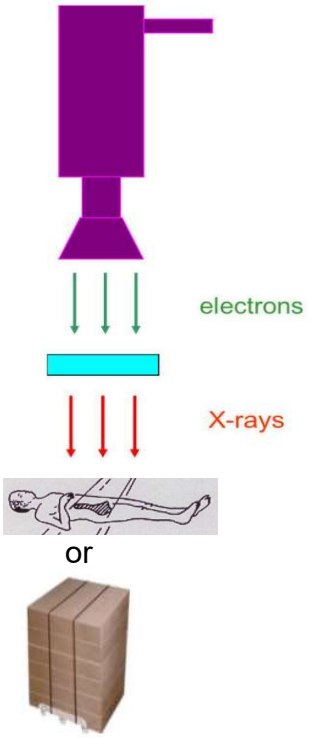
electrons



X-rays



BREMSSTRAHLUNG
PHOTONS
braking radiation



Bremsstrahlung photons

Electrons

Photoelectric effect

Compton scattering

Pair production

Brems-strahlung production

Collision

Low-energy electrons

ionisation

excitation

chemical reactivity quite low

Ions
free electrons

recombination

dissociate

Excited molecules

recombination

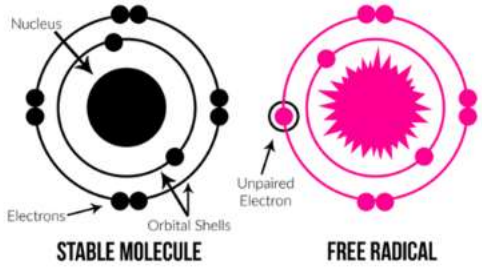
recombination

FREE RADICALS

chemical reactivity very high

FREE RADICALS

Molecules, ions or atoms with an unpaired electron in the outer shell



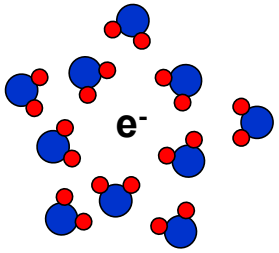
RADIOLYSIS OF WATER (simplified)

$H_2O \rightarrow H_2O^+ + e^-$

$H_2O + e^- \rightarrow H_2O^-$

$H_2O^+ + H_2O^- \rightarrow H^+ + OH^- + H^\circ + OH^\circ$

OH°(aq) ~ 45 % **H°(aq) ~ 10 %** **e^- (aq) ~ 45 %**



$H^\circ + OH^\circ \rightarrow H_2O$

$H^\circ + H^\circ \rightarrow H_2$

$OH^\circ + OH^\circ \rightarrow H_2O_2$

FREE RADICALS

- **damage DNA** — *radiotherapy, food irradiation, sterilisation*
- **chain reaction** — $R^{\circ} + AB \rightarrow R\text{-}AB^{\circ}$; $R\text{-}AB^{\circ} + AB \rightarrow R\text{-}AB\text{-}AB^{\circ}$ — *polymer chemistry*
- **special chemical reactions** — *radiation synthesis*
- **graft a second polymer** — *curing, biomaterials*

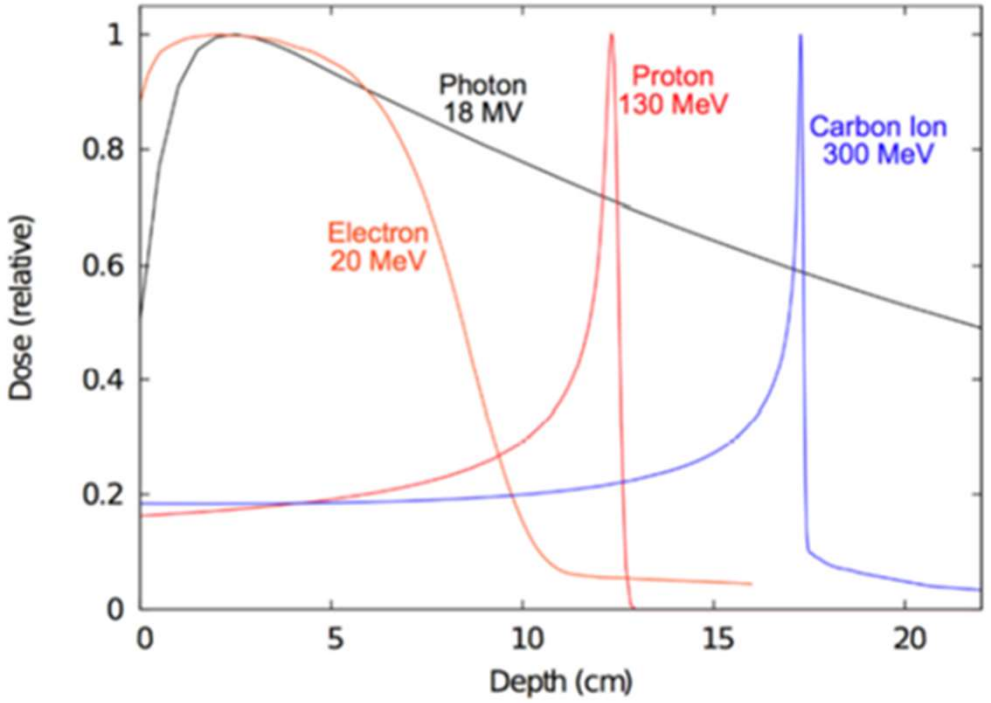
Physical, chemical and biological effects of particles or photons ~ deposited energy

DOSE = deposited energy per unit mass **1 Gray = 1 J / kg**

Effects of ionising radiation are **not** a result of **heat** creation, but of the production of free radicals

4.2 kGy in water → 1° C (*) ⇒ high yields of reactive species at low temperatures

Ionising radiation creates
similar end products (free radicals)
but with different spatial distributions



(*) 1 calorie is energy needed to increase **temperature** of 1 gram of water by 1 C. 1 calorie = 4,1868 joule
4 kG will kill almost all living species in water

Outline

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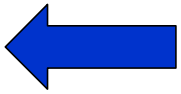
2. Small accelerators for applications

3. Applications in medicine
   - radiotherapy
   - production of radioisotopes

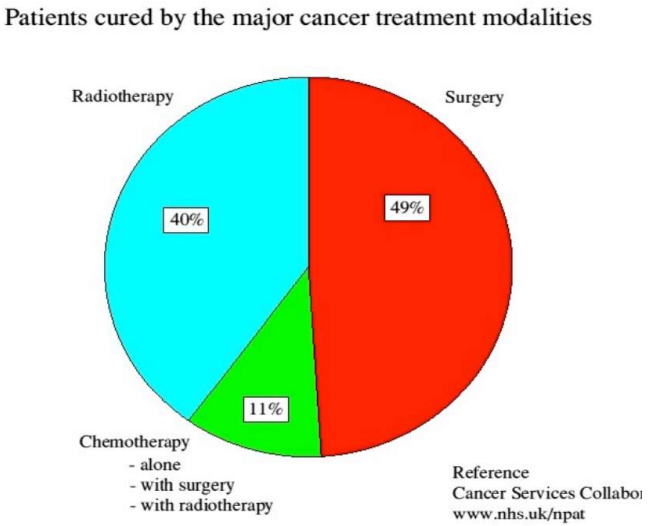


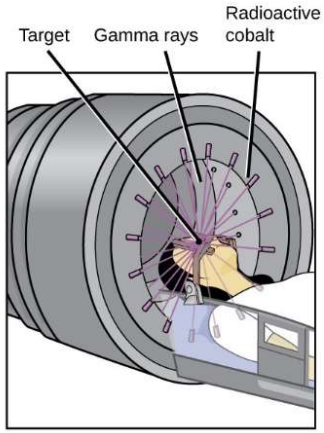
4. Applications in industry
   - radiation processing
   - ion beam applications

5. Analysis of physical, chemical or biological properties of materials
   - with photon or neutron beams
   - with ion beams

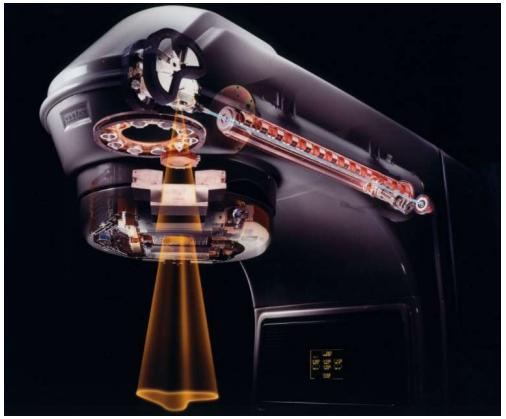
Small particle accelerators for medicine

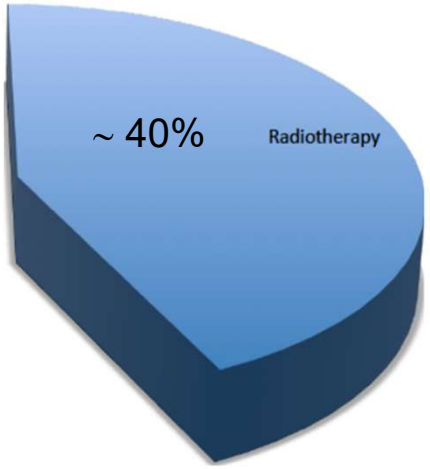
- Radiotherapy
- Nuclear medicine





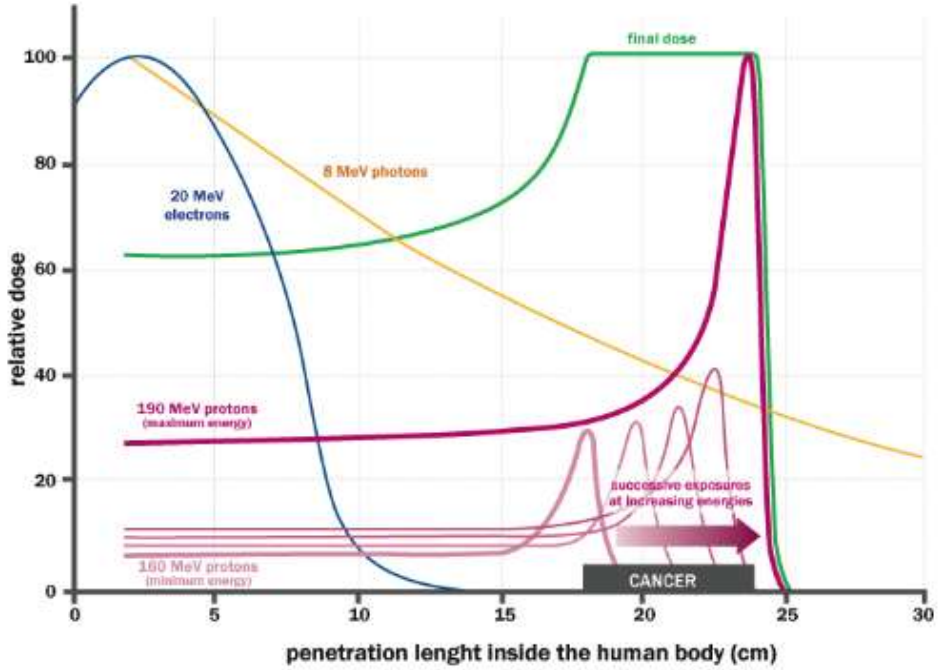
Until 1990: almost exclusively Cobalt sources





Now: almost exclusively electron accelerators

Hadrons versus leptons or photons



Bragg peak

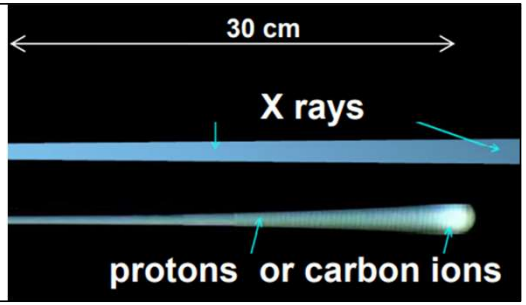
Bethe-Bloch equation of ionisation energy loss by protons and ions

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2}\frac{nz^2}{\beta^2}\cdot\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\cdot\left[\ln\left(\frac{2m_e c^2\beta^2}{I.(1-\beta^2)}\right)-\beta^2\right]$$

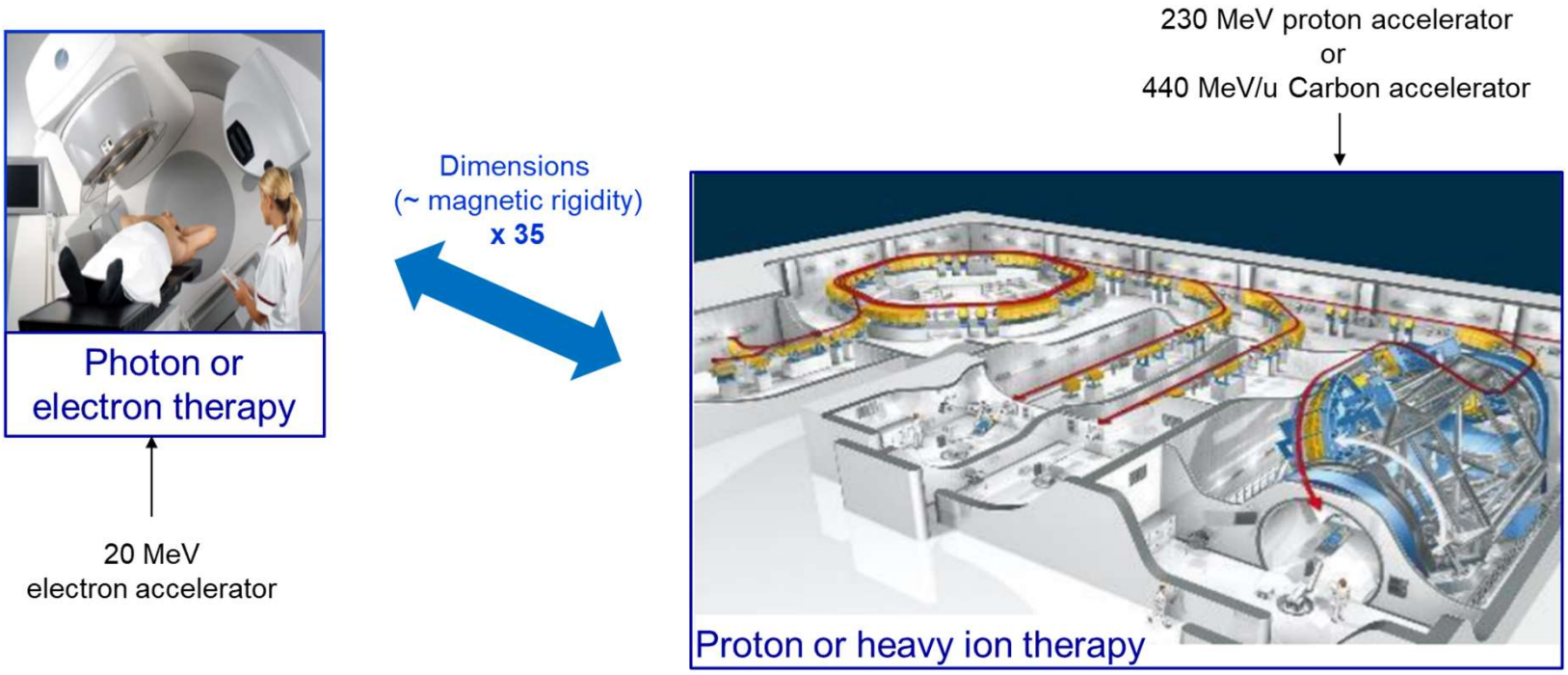
X-rays: 20 MeV

protons: 230 MeV

C ions : 5000 MeV



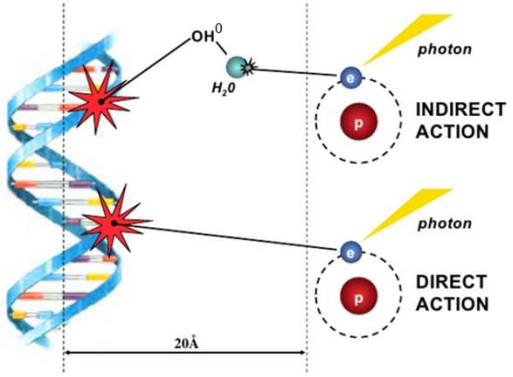
Why remains radiotherapy with photon and electron beams the conventional radiotherapy?



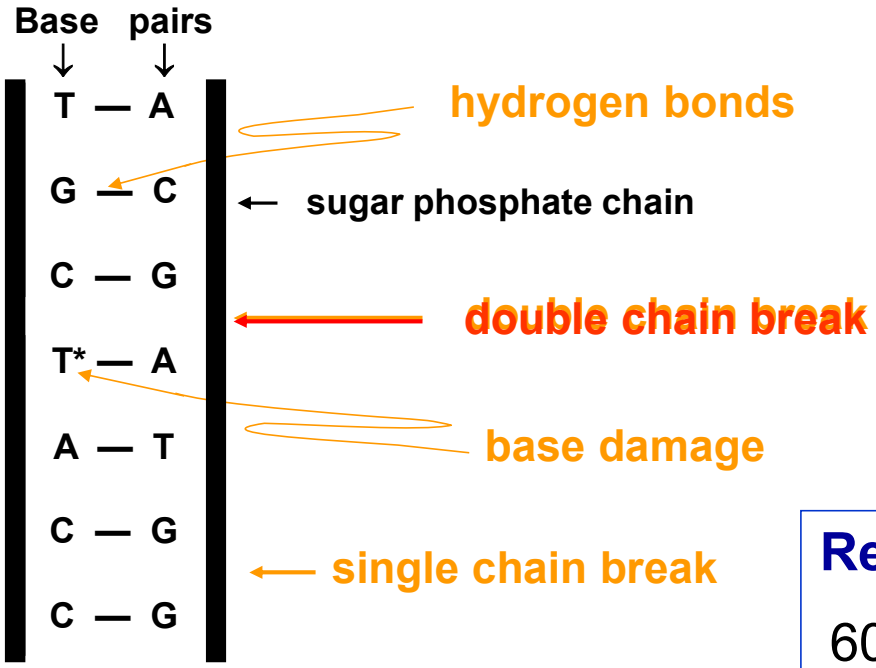
Hadron therapy focuses mainly on treatment of:

- tumours near **critical organs** (base of skull, central nervous system, eyes, head and neck),
- **pediatric tumours** (where surrounding tissues are more delicate and the risk of secondary tumours is higher),
- tumours with cells which are **radioresistant** to X-rays.

Radiotherapy with photon or electron beams

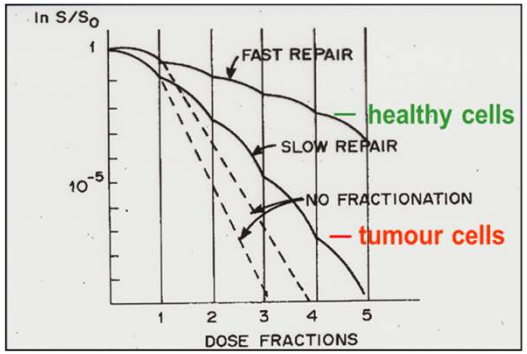


Radiation damage to DNA:
- direct
- indirect by free radicals



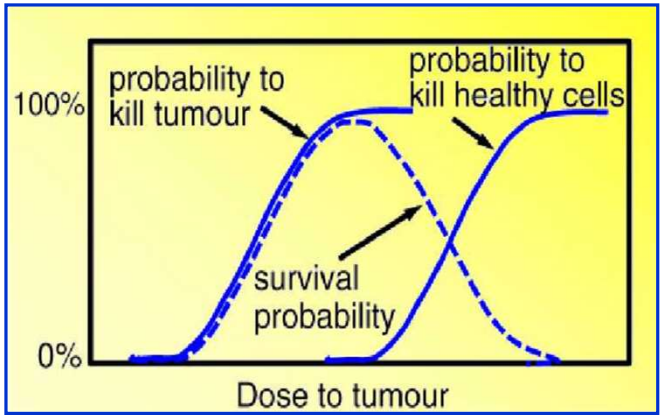
Repair mechanisms

60 Gy lethal for cells



dose delivery is optimized in **time**

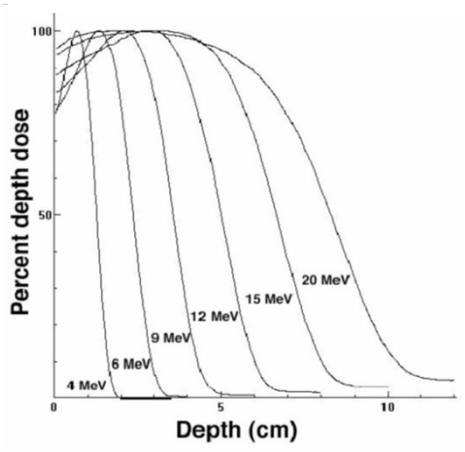
Dose fractionation:
dose delivery typically 30 sessions of 2 Gy
5 days/week, during 6 weeks

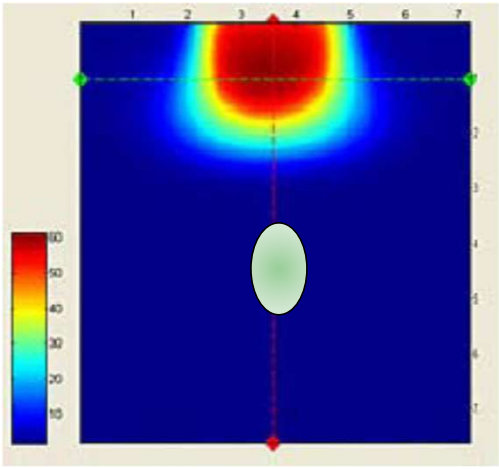


Radiotherapy with photon or electron beams

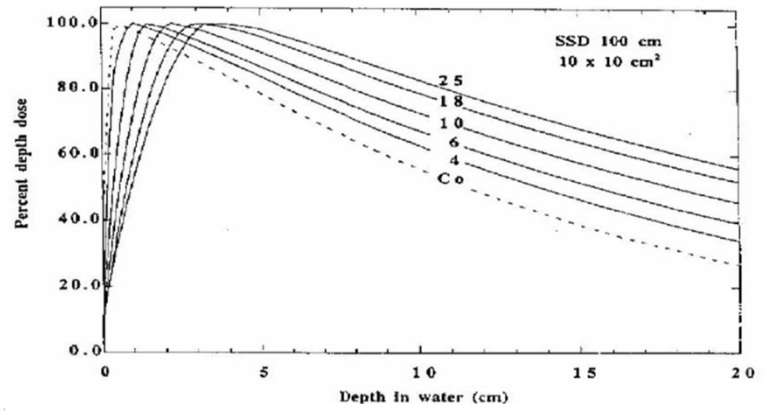
the dose distribution must be optimized in **space**

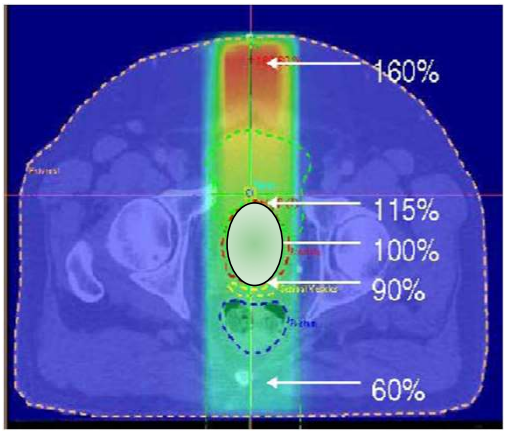
electrons

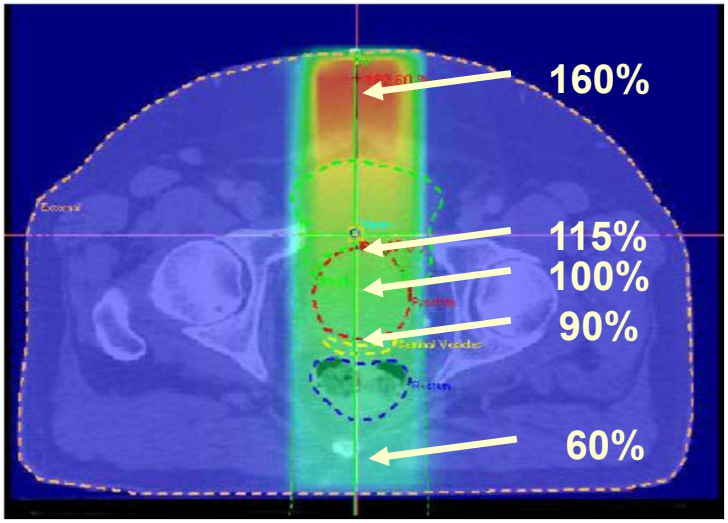




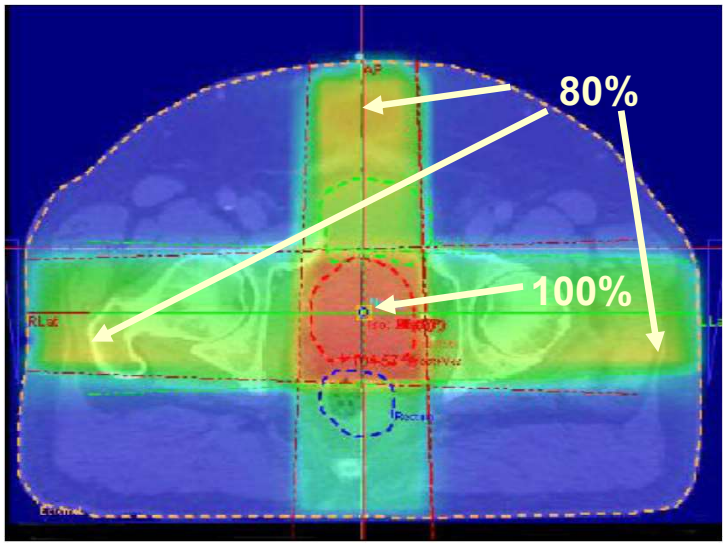
photons



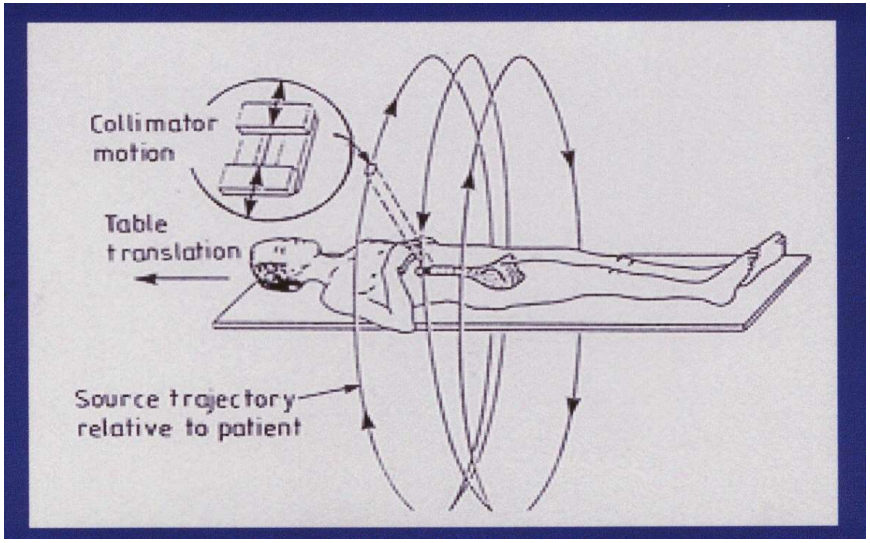


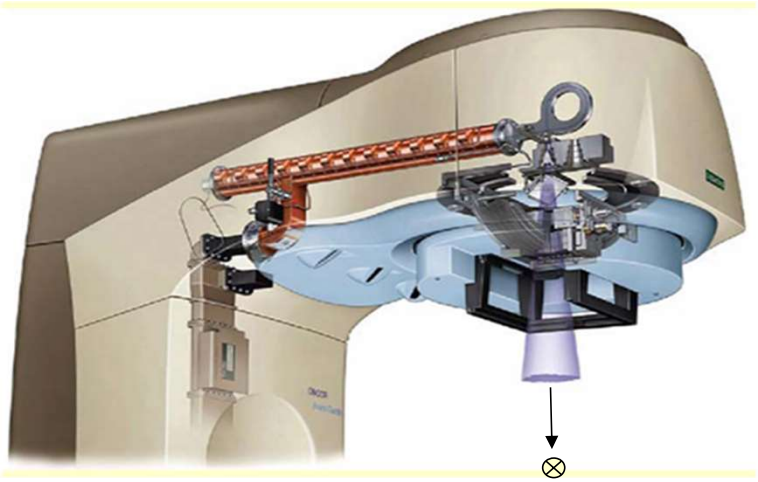


SINGLE BEAM

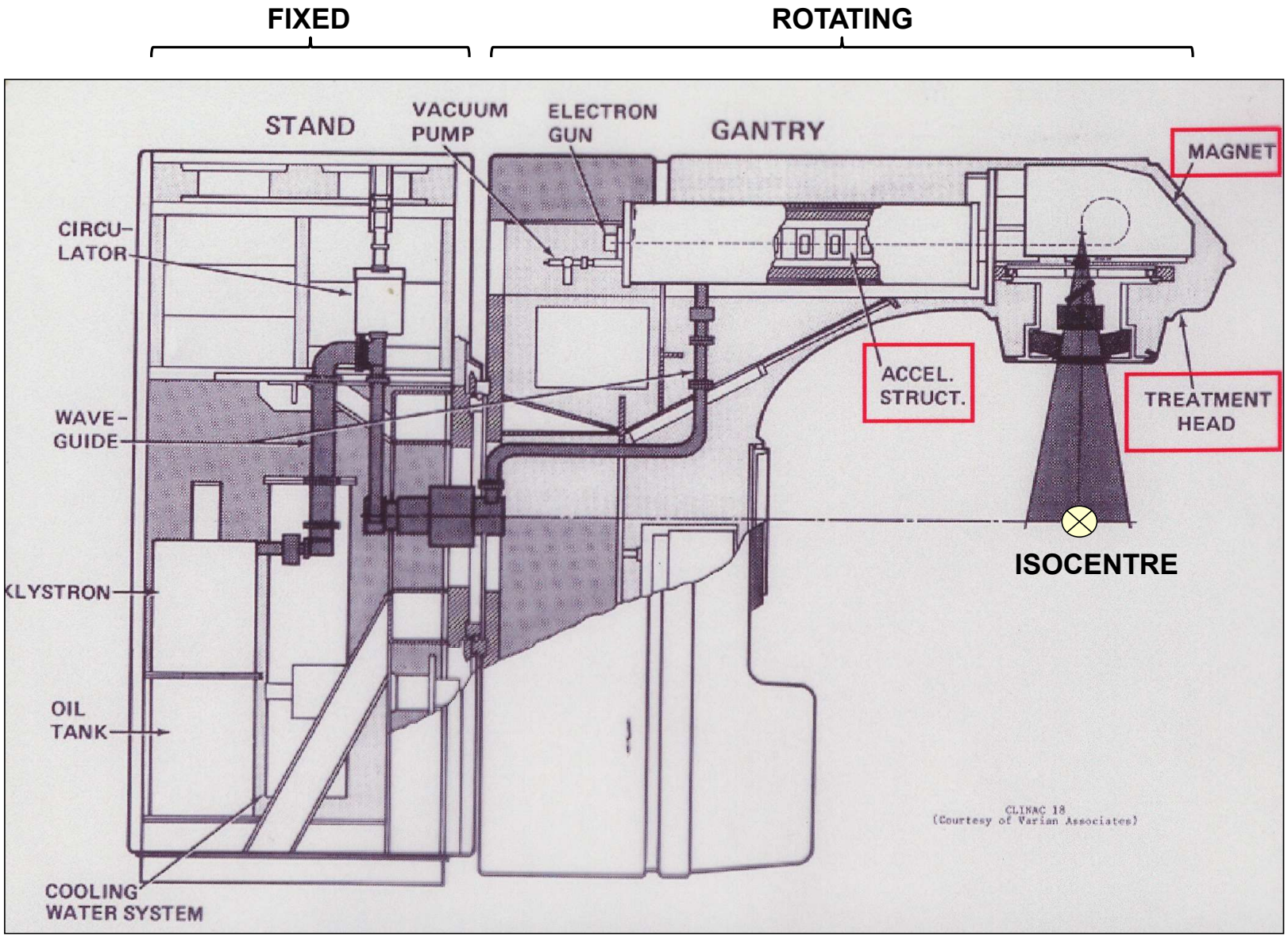


MORE BEAMS

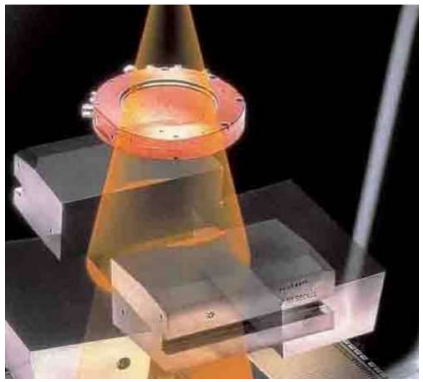


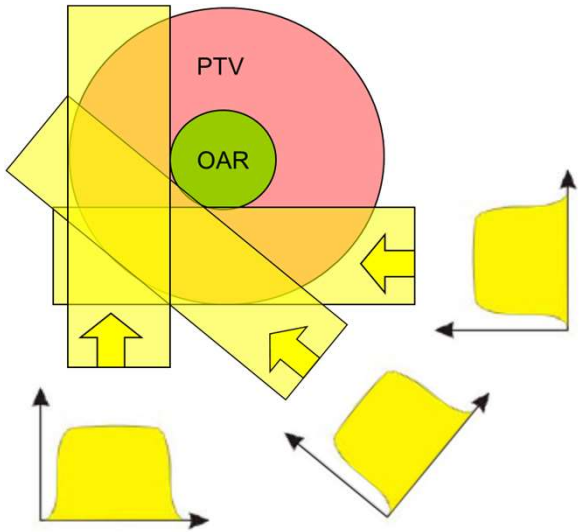


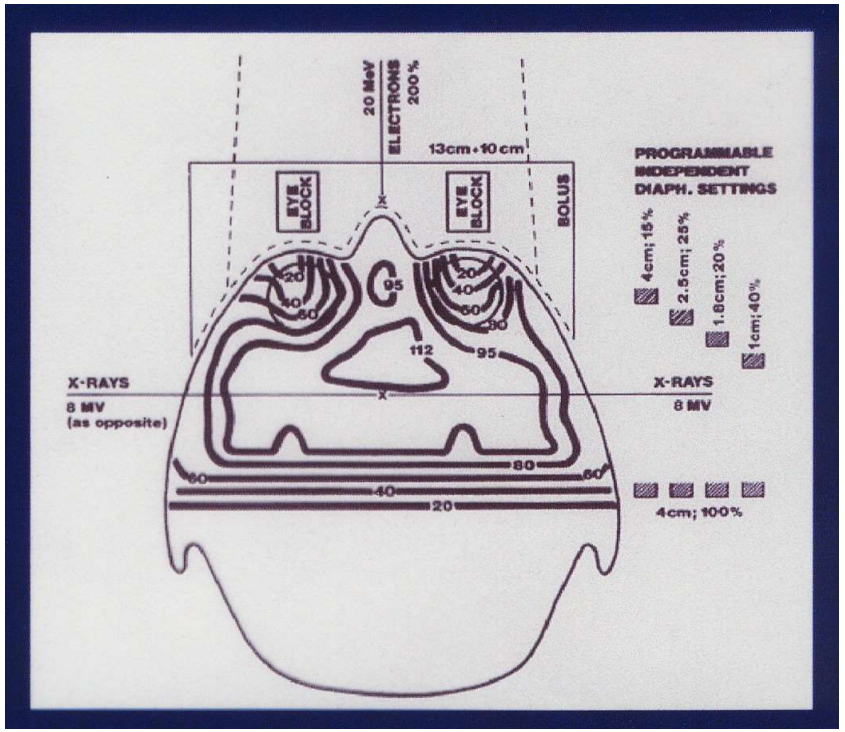
Cross-fire technique


FIXED
ROTATING
STAND
VACUUM PUMP
ELECTRON GUN
GANTRY
MAGNET
CIRCU-LATOR
ACCEL. STRUCT.
TREATMENT HEAD
WAVE-GUIDE
ISOCENTRE
KLYSTRON
OIL TANK
COOLING WATER SYSTEM
CLINAC 18
(Courtesy of Varian Associates)

CLASSICAL APPROACH: combination of rectangular uniform radiation fields



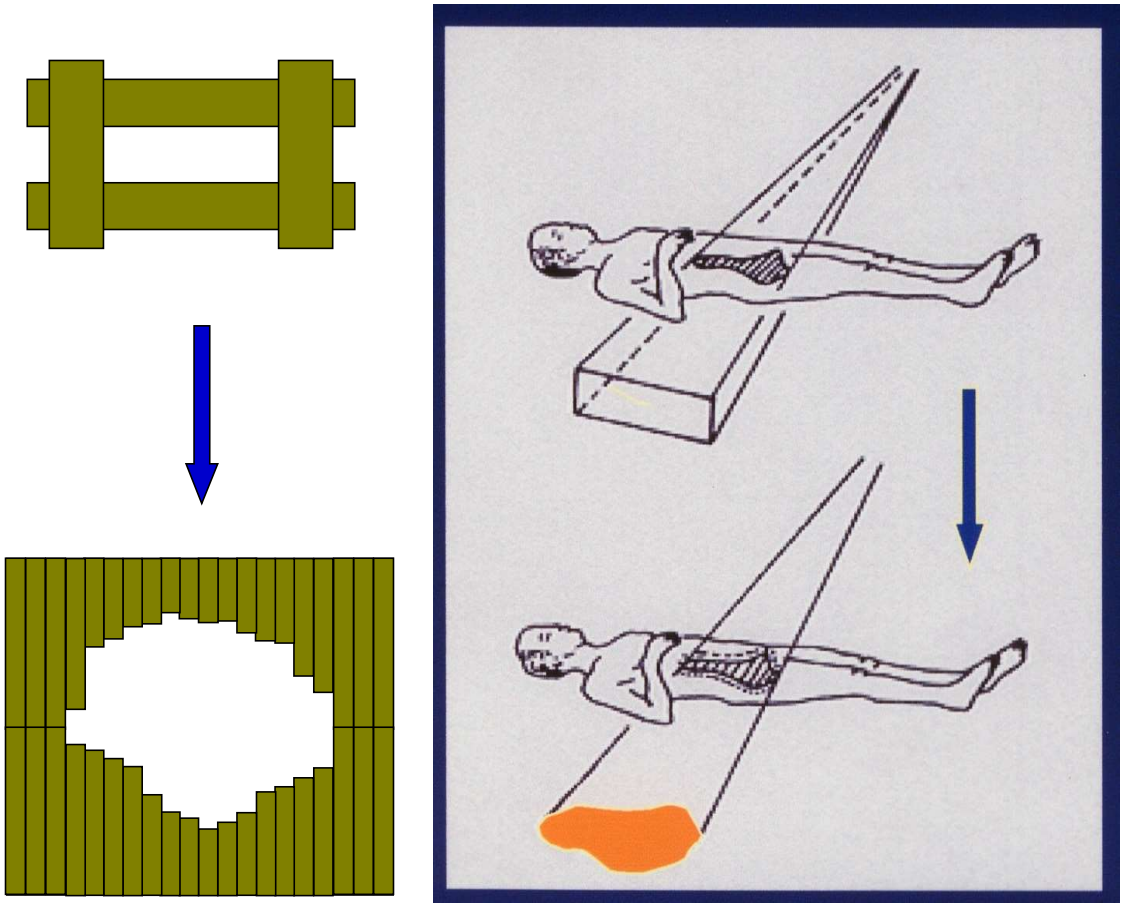




Superposition of 9 beams

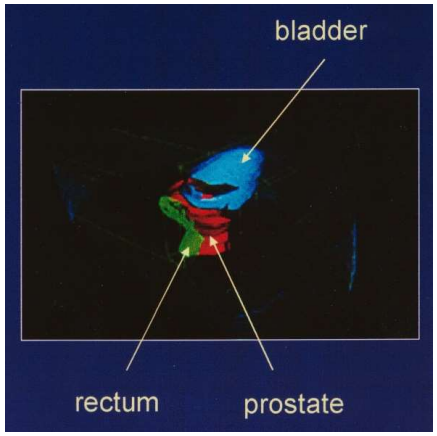
- eight photon beams (8 MeV endpoint) with different width 4 beams from right, 4 from left
- one 20 MeV electron beam from the front

First improvement step: irregular-shaped uniform radiation fields



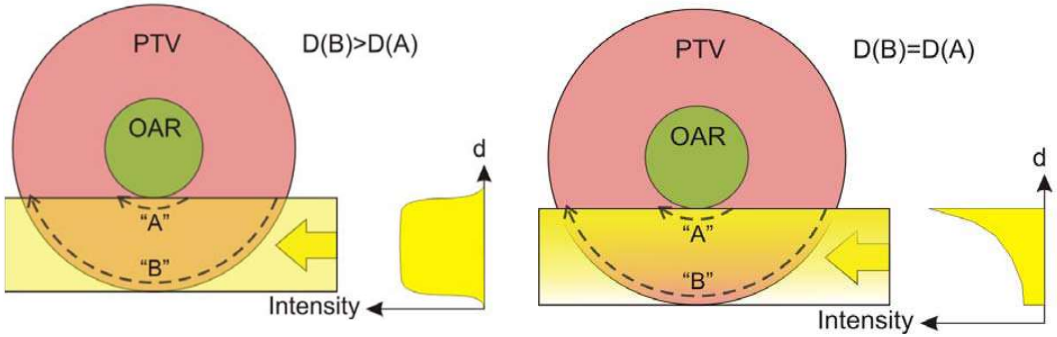
Multileaf collimator

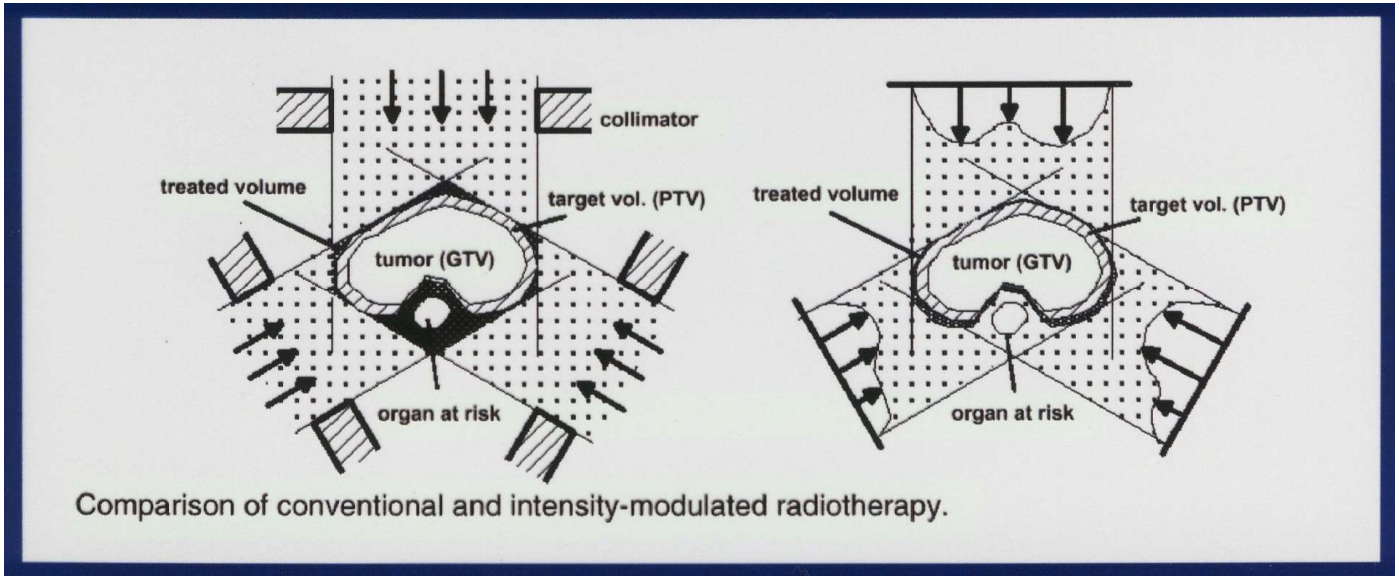
CONFORMAL THERAPY



Second improvement step:
irregular-shaped non-uniform radiation fields

INTENSITY-MODULATED RADIOTHERAPY - IMRT

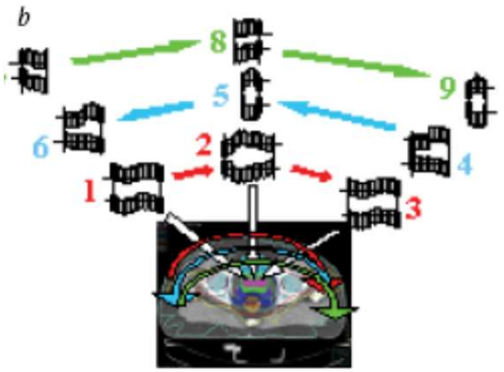


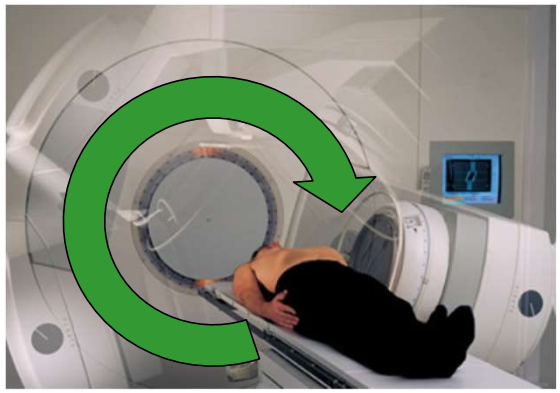


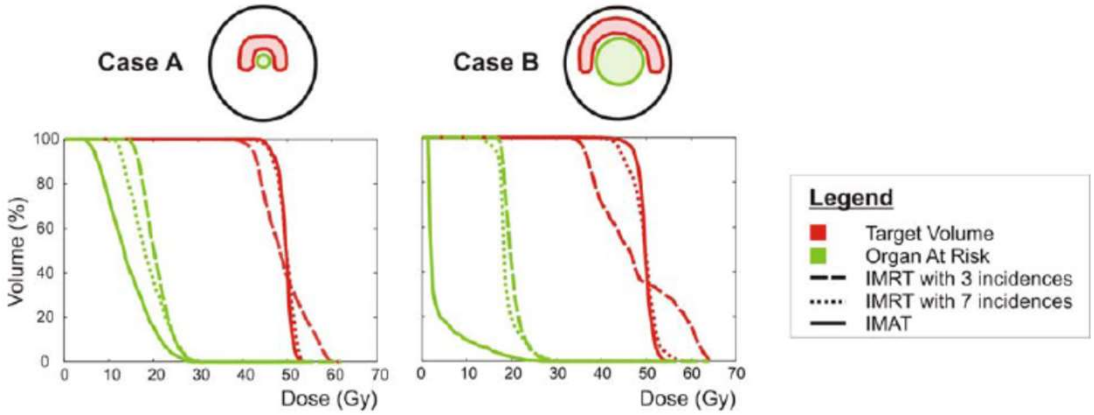
Comparison of conventional and intensity-modulated radiotherapy.

Third improvement step:
IMRT not from discrete number of directions, but <u>continuously</u> during rotation of gantry

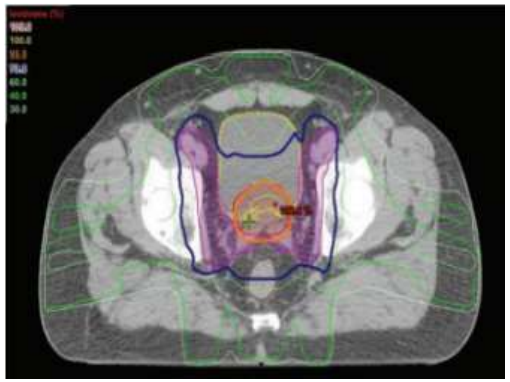
INTENSITY-MODULATED ARC THERAPY - IMAT



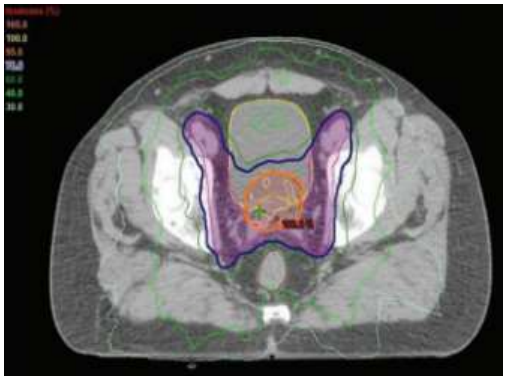




Irradiation of prostate and pelvic nodes while sparing bladder and rectum



IMRT



IMAT

the better the dose conformity, the higher the risk for **over/underdose** due to misalignment of beam!

Positional changes of tumour volume:

- during irradiation

- between fractions

- due to shrinkage of tumour

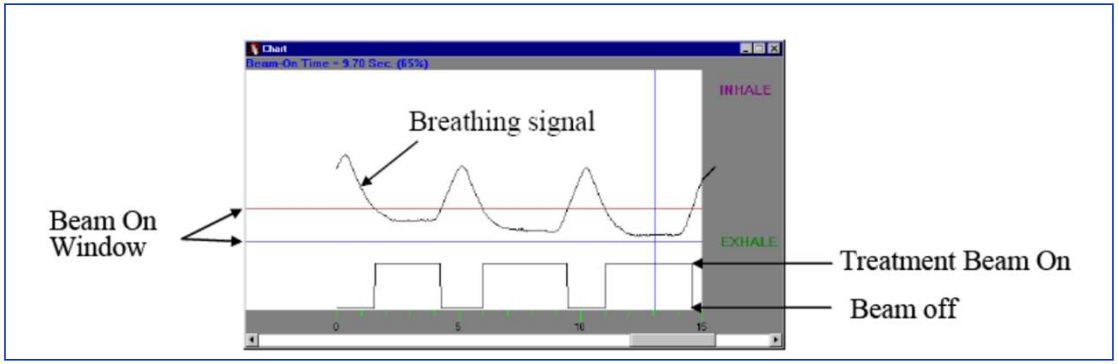


Image-guided radiotherapy with integrated CT imaging (IGRT-CT)

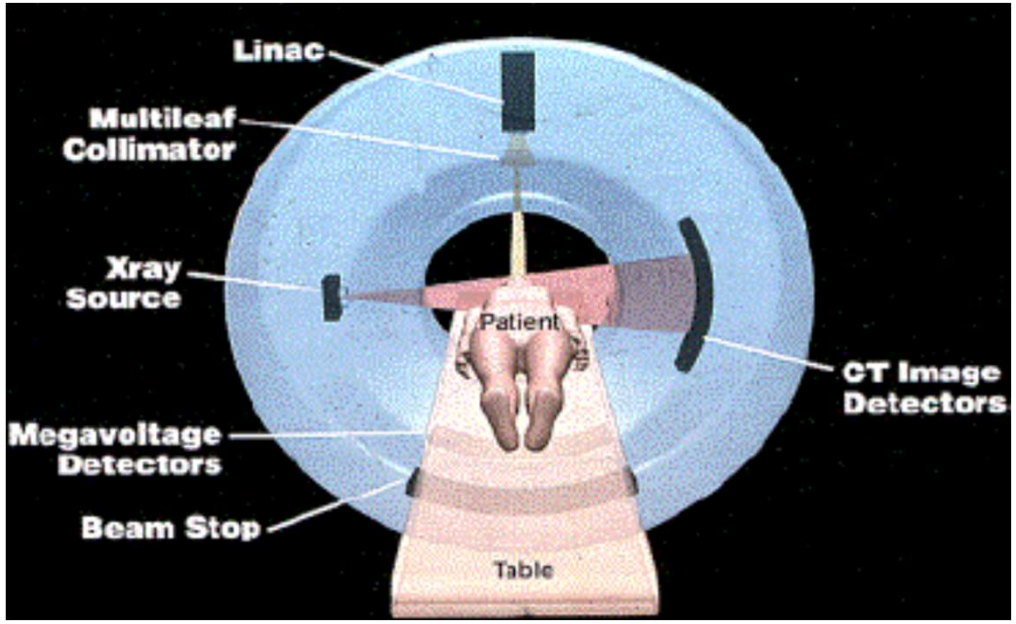
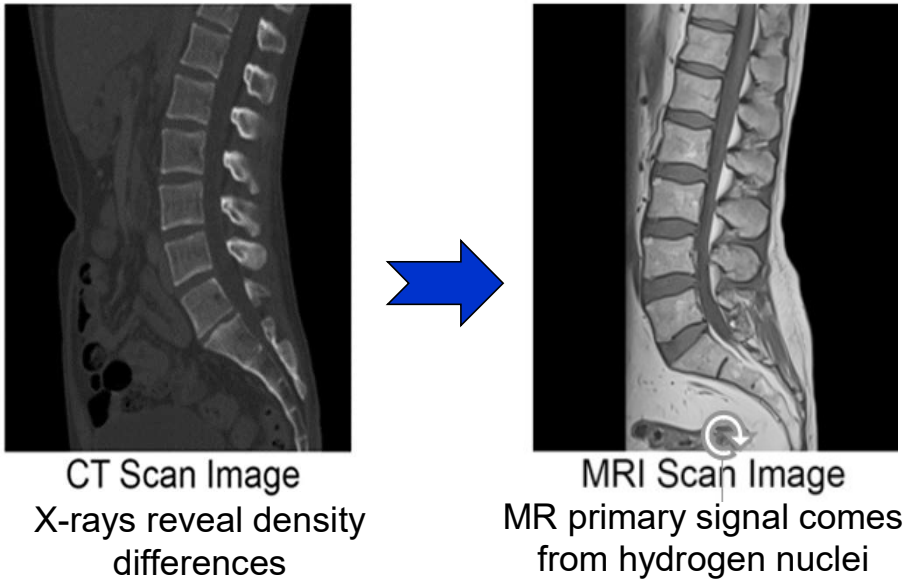
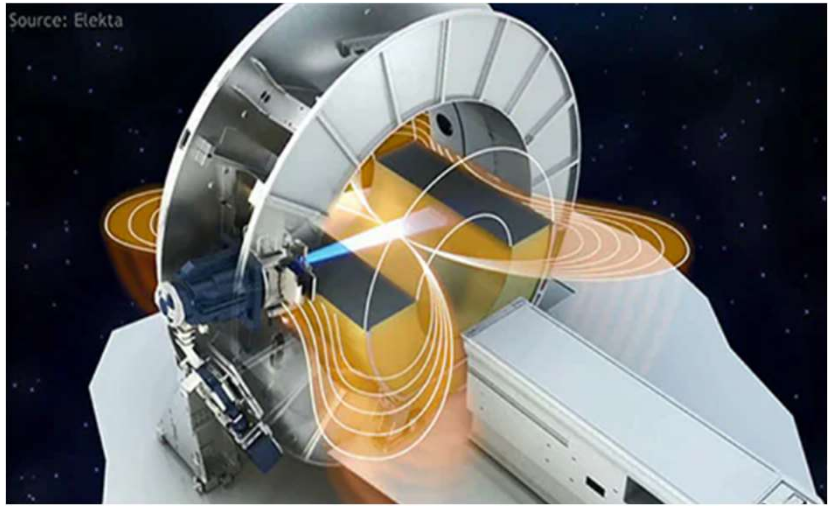


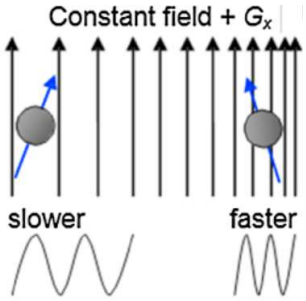
Image-guided radiotherapy with integrated MR imaging (IGRT-MR)



2T MRI magnet and 6 MeV linac

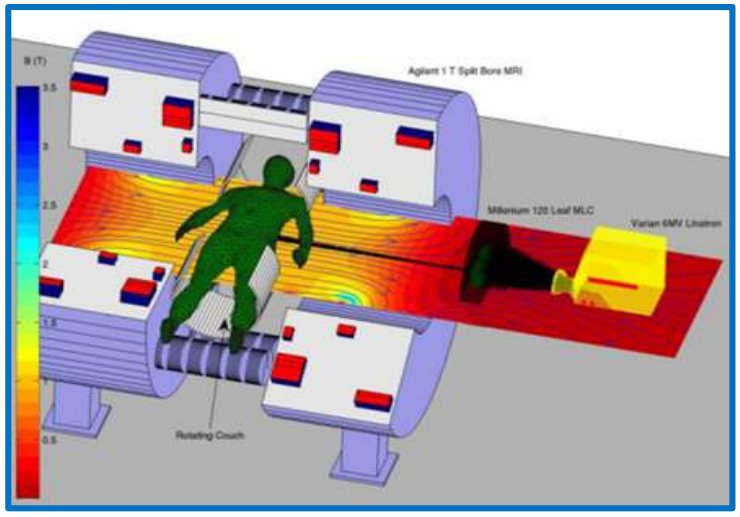


MRI scanners use strong magnetic fields, magnetic field gradients, and radio waves to detect hydrogen nuclei and to generate images of the organs in the body



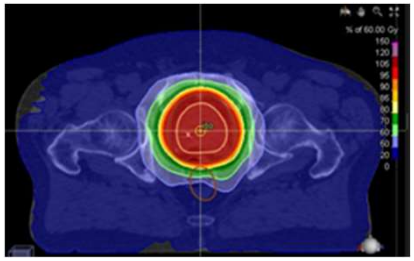
Advantages:

- Excellent soft-tissue imaging
- Differentiation cancerous from healthy tissue
- Faster real-time imaging during treatment
- Very high image quality
- Ability to see the tumor on-line
- Non-ionising imaging



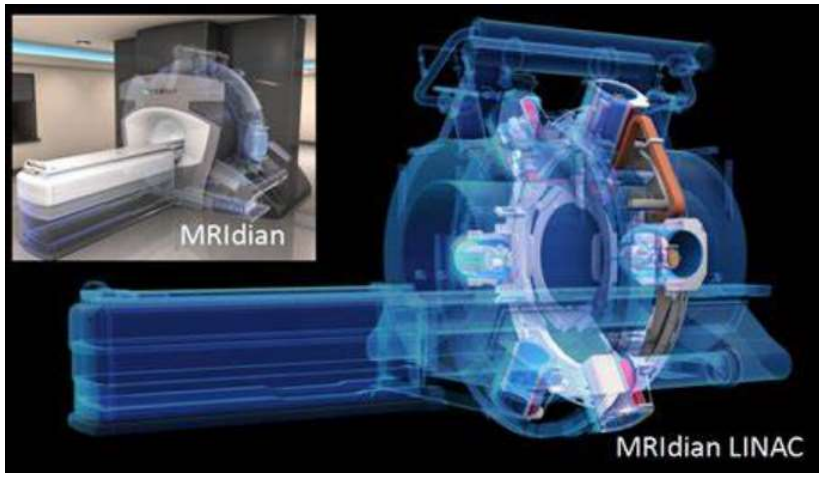
Universitair Ziekenhuis Brussel

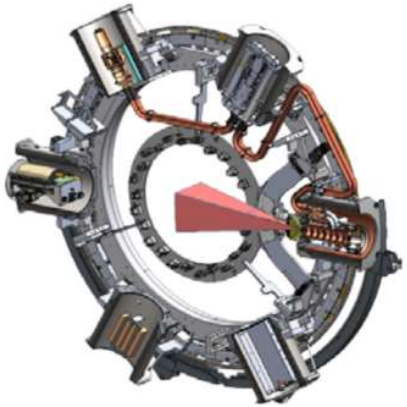
UZ Brussel

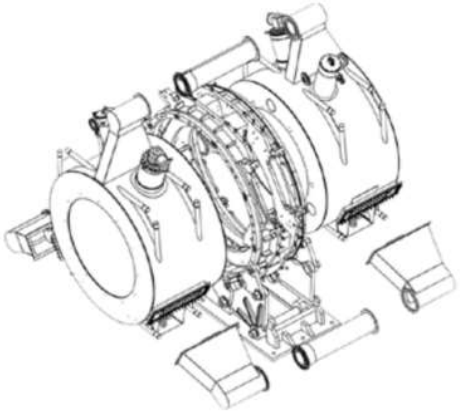


Linac
MRI-Guided Therapy System UZ Brussels

Started in June 2021







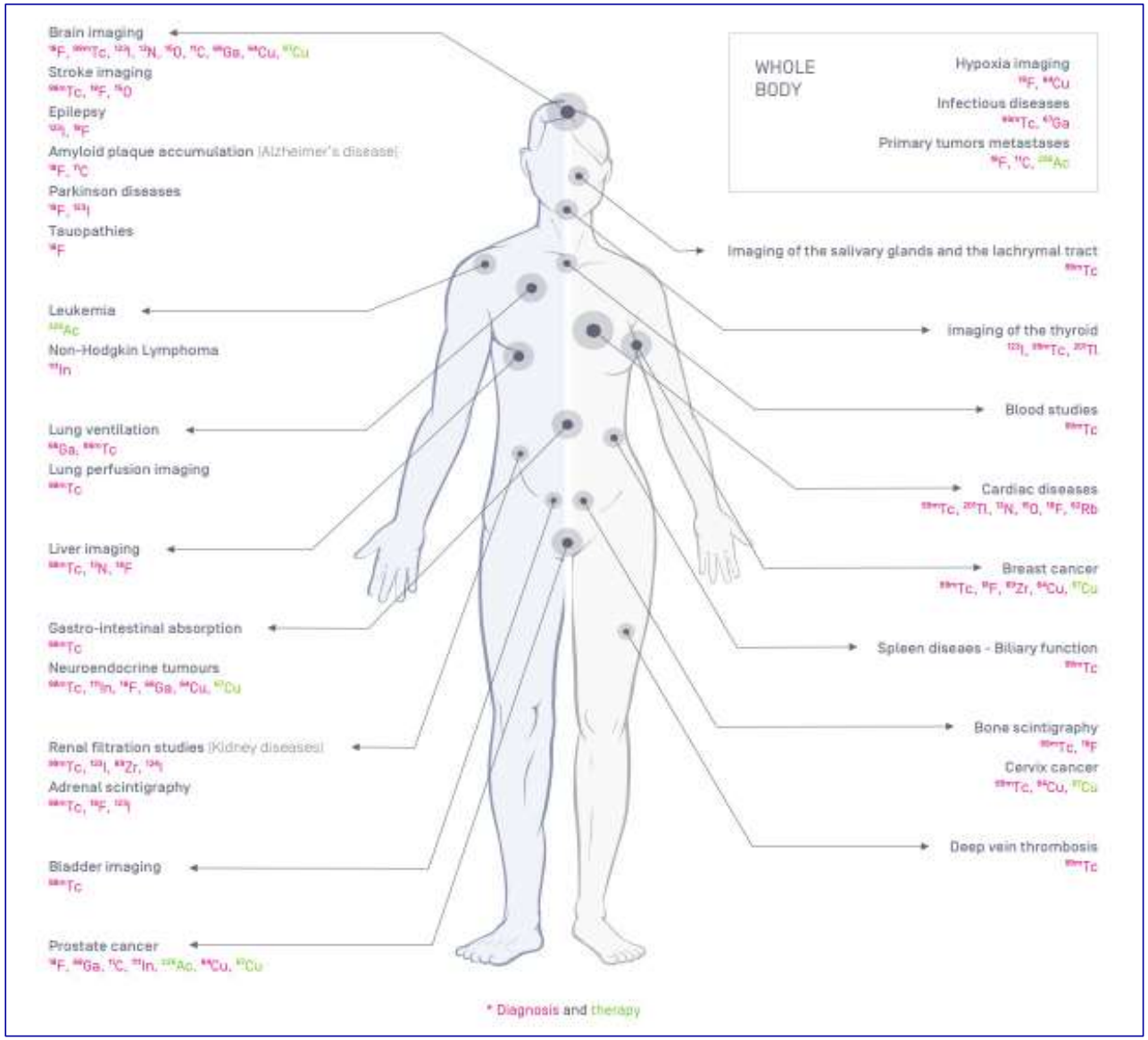
2. Small accelerators for medicine

Radiotherapy

- Photon and electron therapy

Radioisotope production

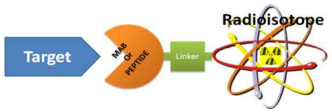
- for medical diagnostics
- for therapy with radionuclides



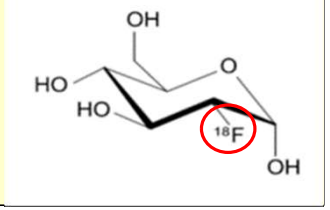
Radioisotopes used in medicine

Uses of medical radioisotopes

- Imaging: 95 %
- Therapy: 5 %



Radioisotope attached to a normal **chemical compound**, usually a glucose (Fludeoxy-glucose (FDG) molecules).



Compound is injected to the patient and accumulates in tissues with **high metabolic activity**, as tumours and metastasis.

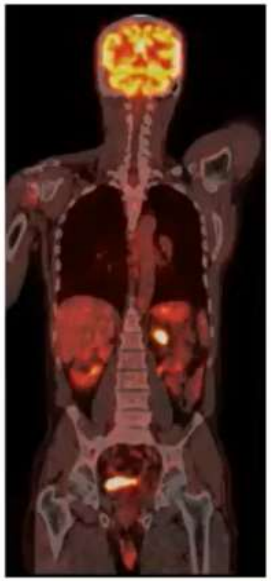
When the radioisotope decays, depending on the isotope, the emitted radiation is

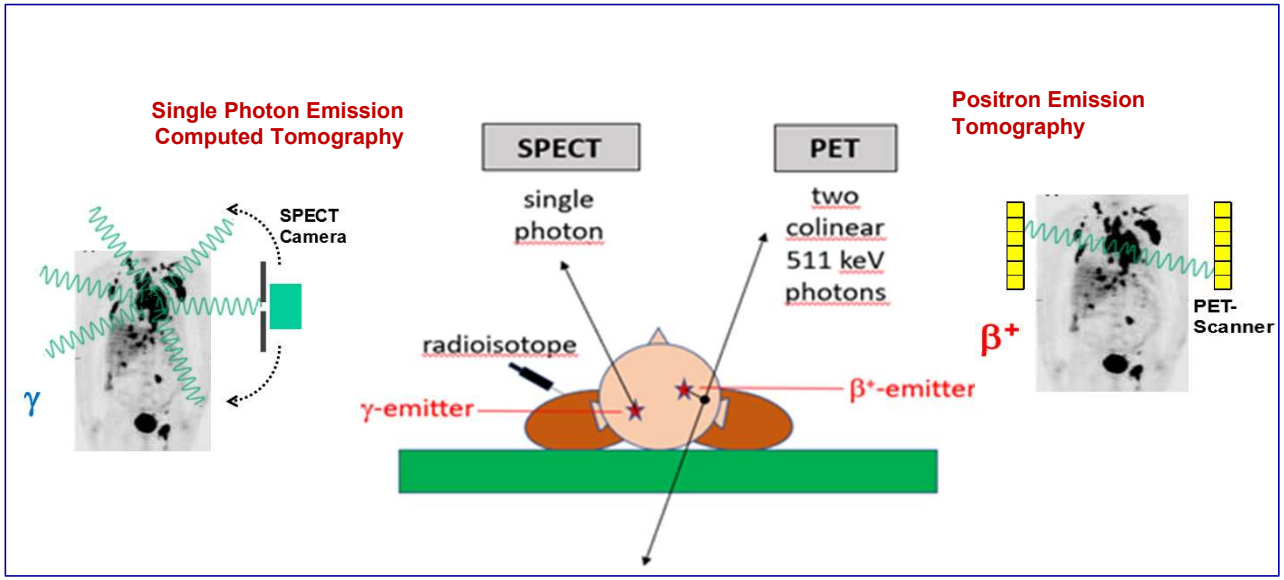
(1) detected by a scanner allowing a precise mapping of the emitting areas **(= imaging)**.

(2) absorbed locally, inside a tumour **(= therapy)**

Radioisotopes for medical diagnostics

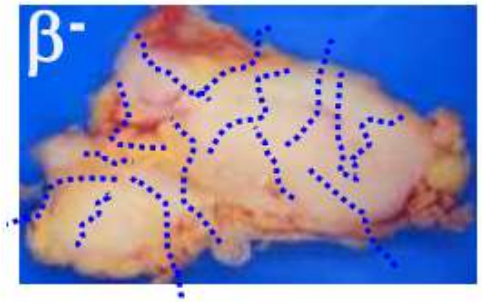
detection outside of human body → γ emitters : **SPECT (^{99m}Tc, ^{123}I , ^{111}In…)**
→ β^+ emitters : **PET (^{18}F, ^{11}C, ^{13}N, ^{15}O…)**

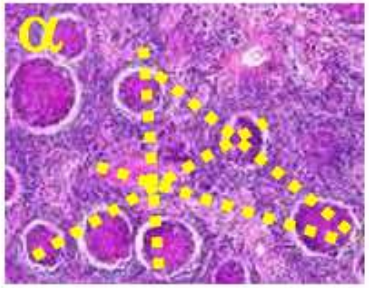


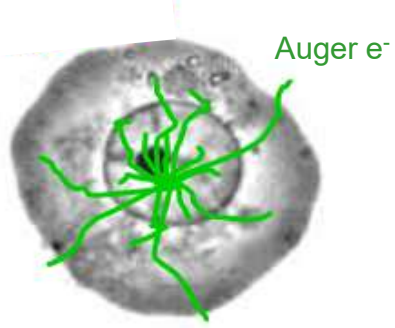


Radioisotopes for medical therapy

local dose deposition inside tumour → α emitters : (^{211}At, ^{213}Bi, ^{225}Ac…)
→ β^- emitters : (^{131}I, ^{177}Lu, ^{90}Y…)







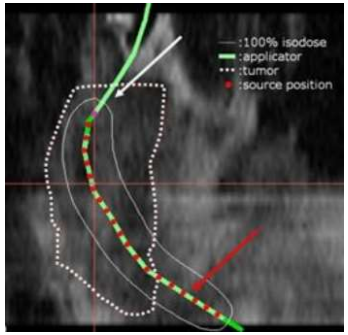
Targeted α therapy (^{211}At, ^{213}Bi, ^{225}Ac)

Alpha-emitting therapeutic isotopes, **radioimmunotherapy**

- **Injected radiolabeled antibodies** accumulate in cancer tissues and selectively deliver their dose.
- Particularly effective with **alpha-emitting radionuclides** (minimum dose on surrounding tissues).
- Very promising for solid or diffused cancers (leukaemia).

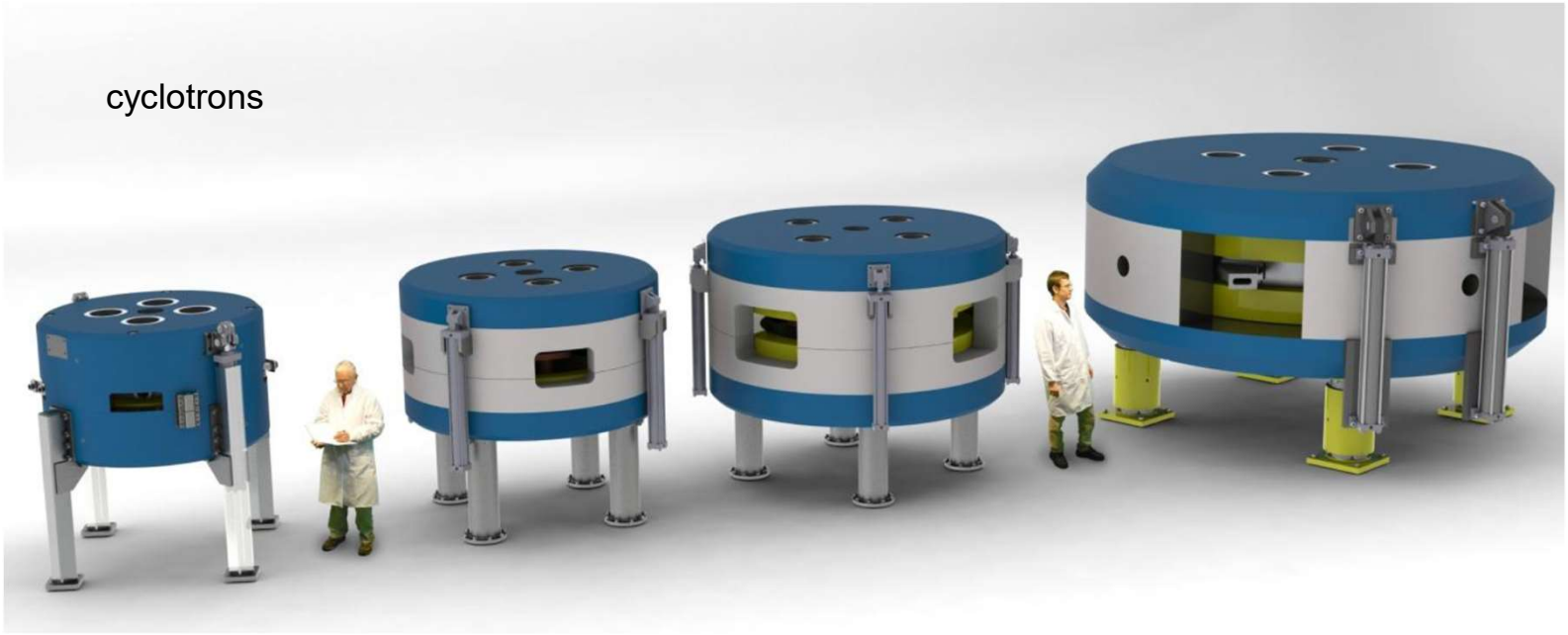
Brachytherapy (^{103}Pd)

A sealed radiation source is **placed physically** inside or next to the area requiring treatment

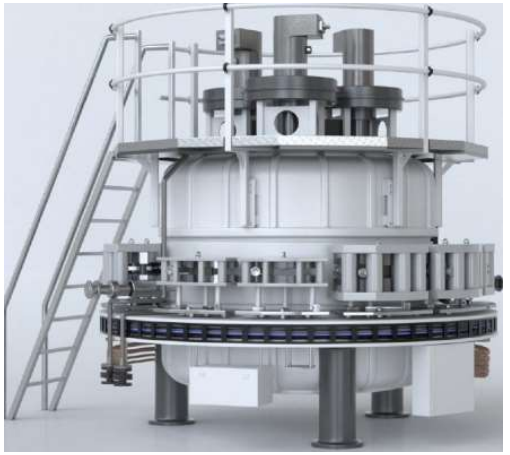


Accelerators used for production of major medical isotopes

- protons, deuterons or alphas (12 to 30 MeV):
  - cyclotrons
  - drift-tube accelerators
- electrons (up to 40 MeV) for bremsstrahlung production:
  - LINACs
  - Rhodotrons



linacs



rhodotrons

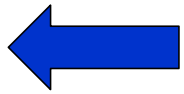
Outline

1. Introduction

2. Small accelerators for applications

3. Applications in medicine
   - radiotherapy
   - production of radioisotopes

4. Applications in industry
   - radiation processing
   - ion beam applications



5. Analysis of physical, chemical or biological properties of materials
   - with photon or neutron beams
   - with ion beams

Particle Accelerators for

1. Medicine

2. Industry

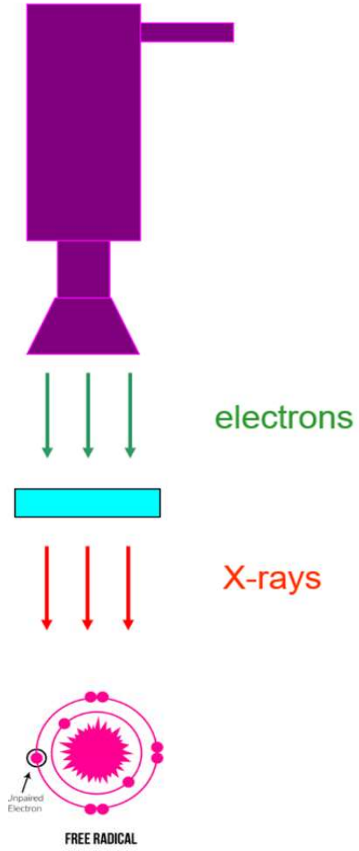
3. Accelerator based analytical techniques

electrons
X-rays

- **Radiation processing**
- **Ion beam applications**

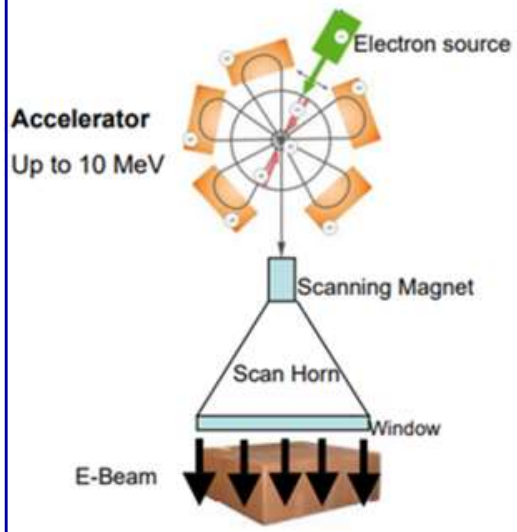
ions

- Polymer chemistry
- Sterilisation
- Food treatment
- Environment
- Materials processing



Radiation (ions, electrons, X-rays) is directed into a material **to change its physical, chemical, or electrical properties**

Electron beam



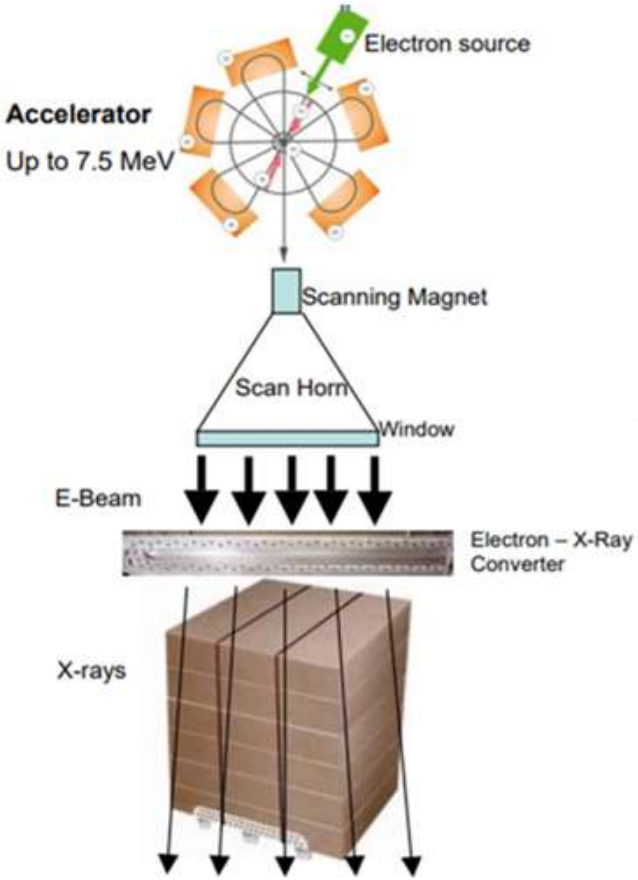
World Health Organisation

Max. energies:

7.5 MeV photons
10 MeV electrons

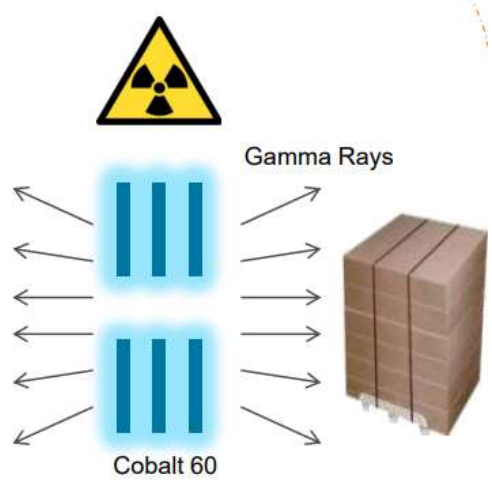
Nuclear reactions
Activation

Bremsstrahlung beam



Bremsstrahlung production efficiency
9,5% at 5 MeV
13,3% at 7,5 MeV

Cobalt source 3 MCi



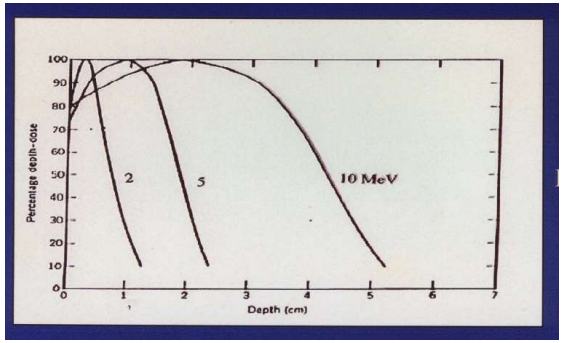
Cobalt source
3 MCi → 45 kW photons

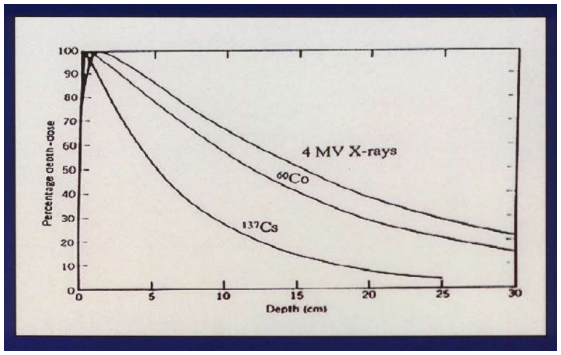
Photon beam from electron beam
at 5 MeV 475 KW → 95 mA
at 7,5 MeV 340 KW → 45 mA

Homogeneity of dose delivery

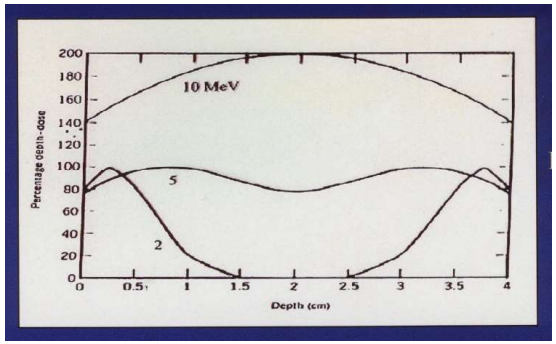
ELECTRONS **in water** **PHOTONS**

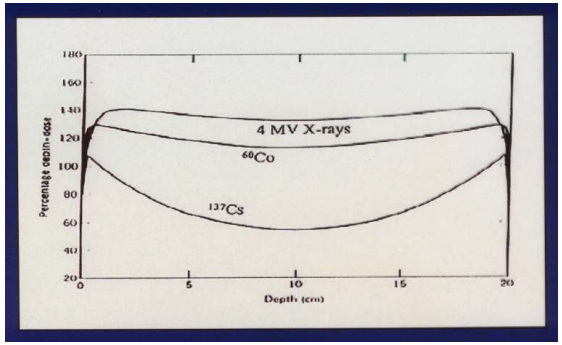
Single-sided irradiation

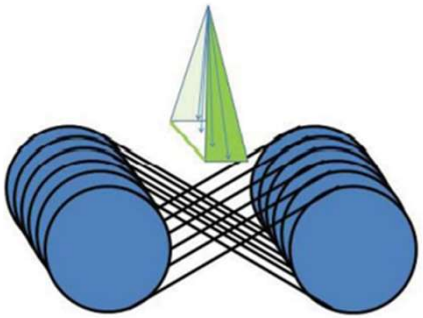


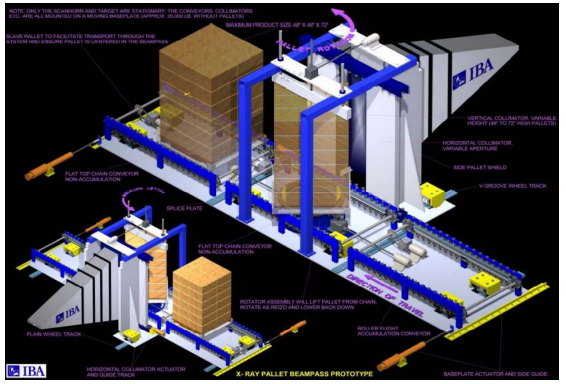


Double-sided irradiation

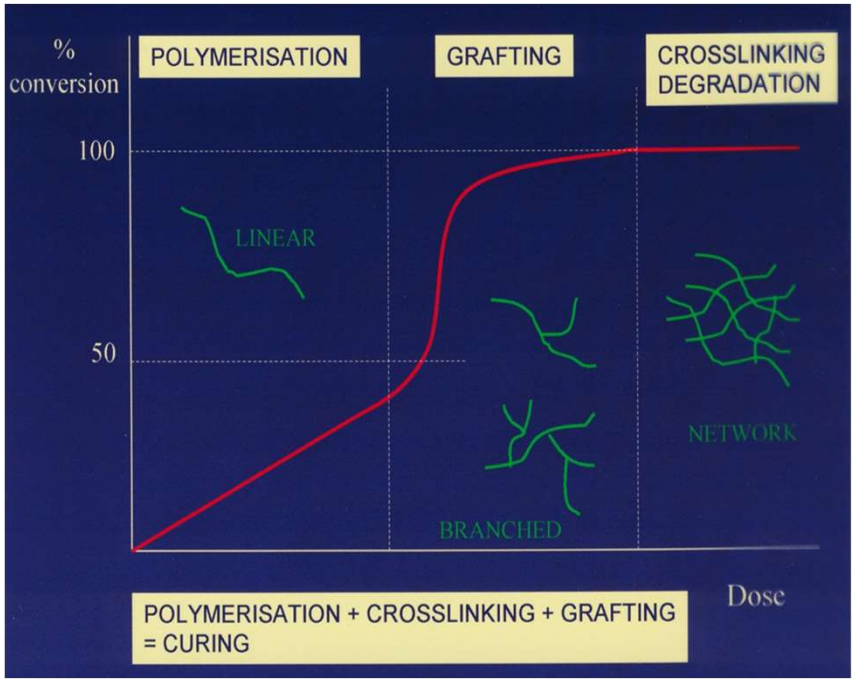




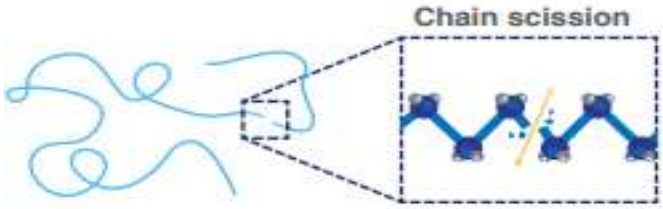




Polymer chemistry



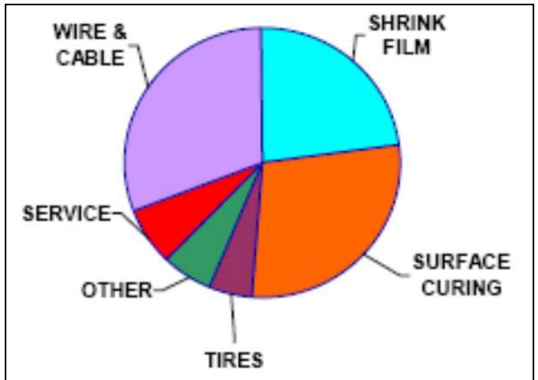
CROSSLINKING POLYMERS



SLICING POLYMERS

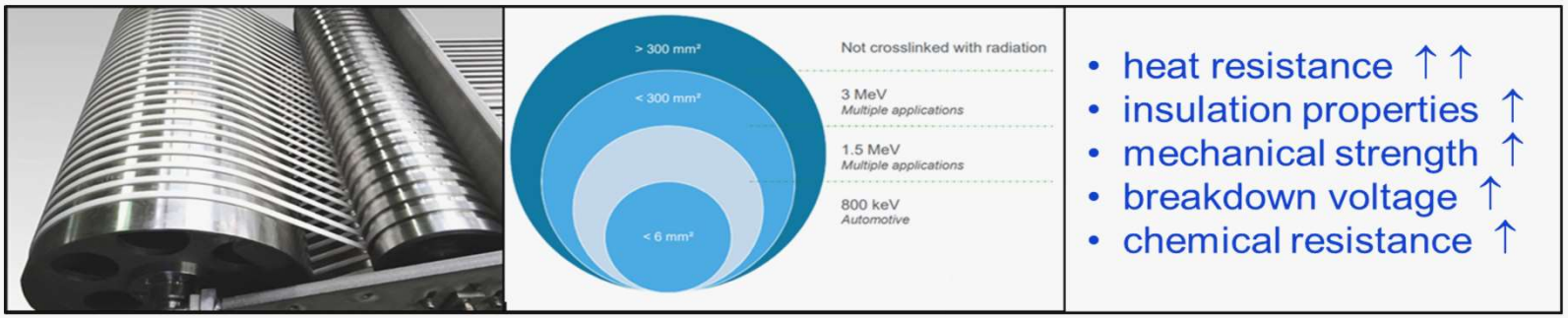
GRAFTING POLYMERS

Irradiation produces
NEW polymer structures
with NEW properties

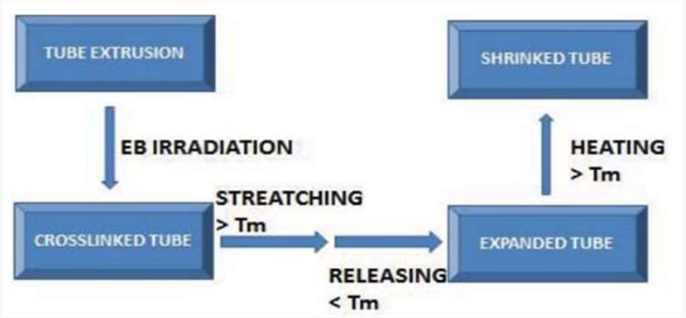


Total of $50 billion per year

Examples of applications of crosslinking

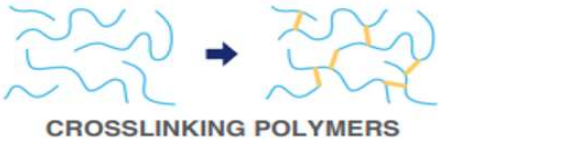


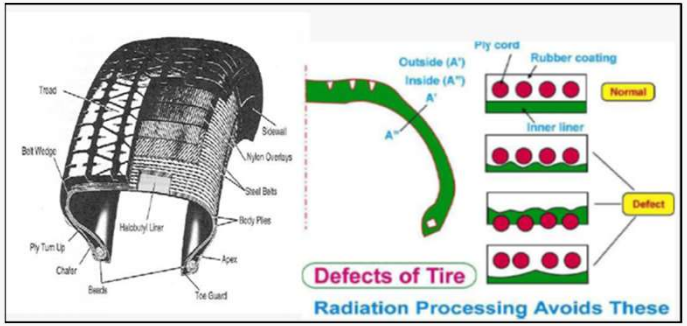
cable insulation



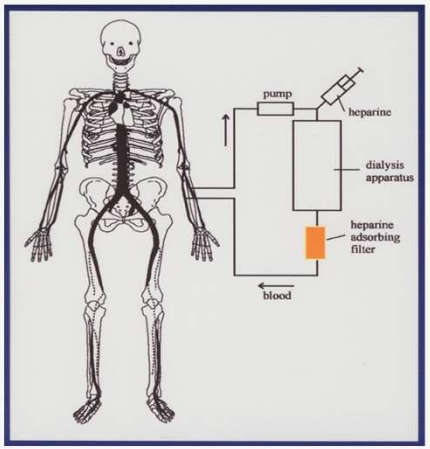
shape-memory effect

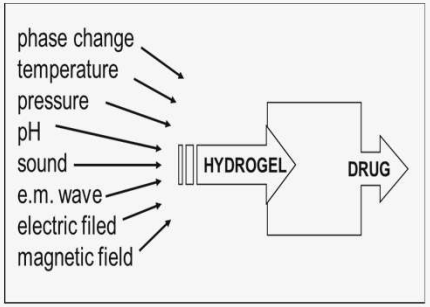
tubes, pipes and mouldings
heat-shrinkable films





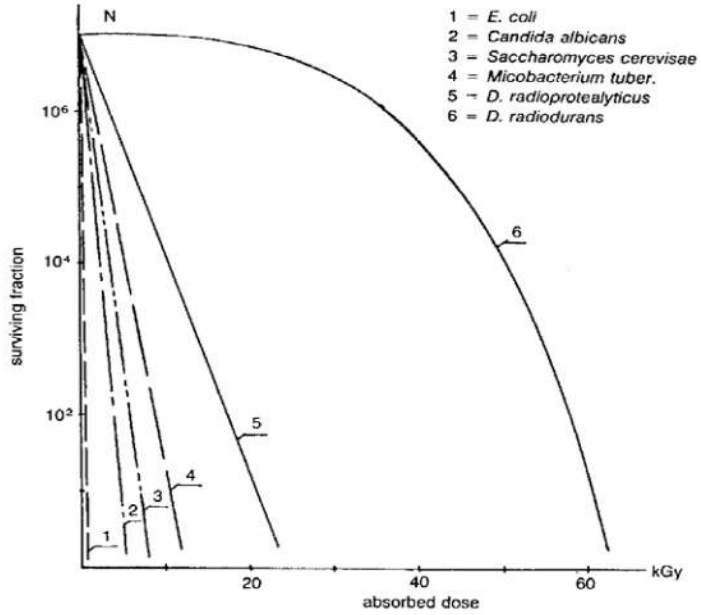
vulcanisation of rubber and tires





synthesis of biomaterials

Sterilisation



Food irradiation

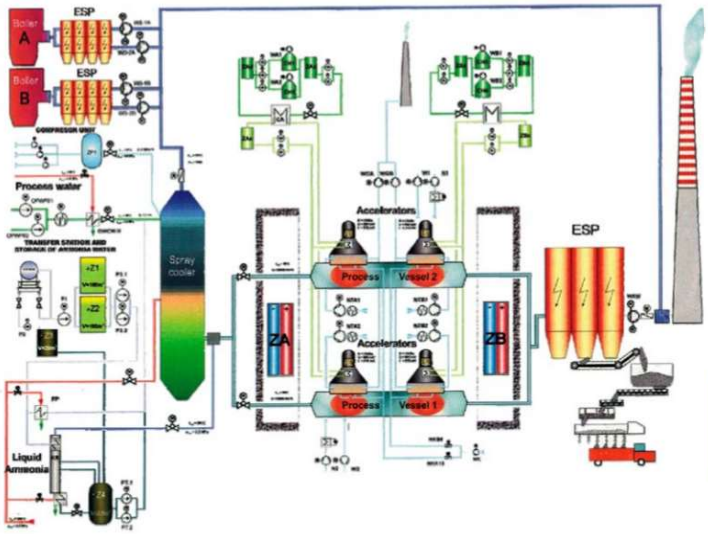
Foods authorised for irradiation in the EU:

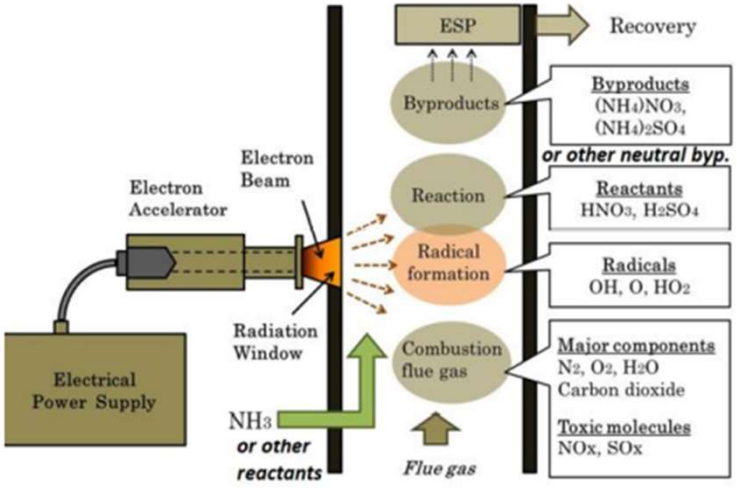
Lower dose → Higher dose

Environment

Degradation of pollutants in water, air and soil

- high-efficiency removal of NO_X and SO_X from flue gases
- treatment of marine diesel exhaust gases
- purifying drinking water
- treating industrial or hospital waste water
- disinfecting sewage sludge
- remediation of Hydrocarbon contaminated soils

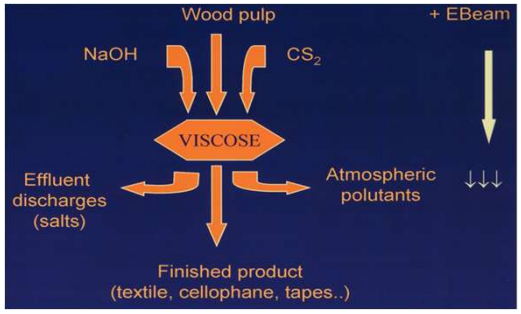




projects in Poland, Japan, USA, Germany, and China

Reduction of pollution by polymer degradation

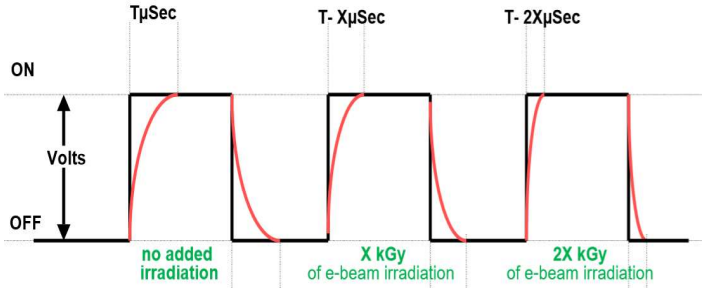
- powdered Teflon for lubricants, high quality inks
- cellulose in viscose industry
- wood pulp in paper industry

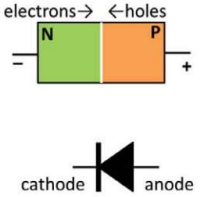


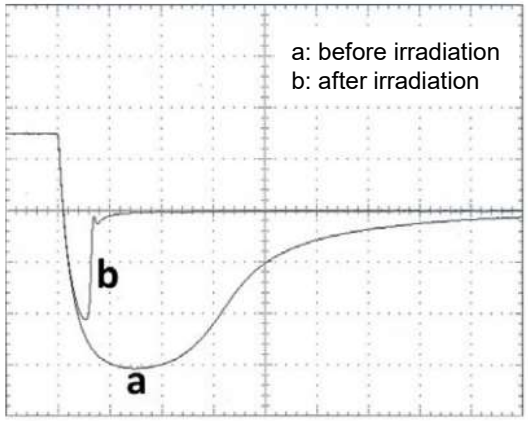
MATERIALS PROCESSING

Improvement of switching speed and recovery times, and other electrical properties of semiconductors

decrease of the lifetime of minority carriers







Switching off characteristic of diode

- fast recovery diodes,
- power diodes
- bipolar power transistors,
- power MOSFETs
- power rectifiers,
- IGBT's,
- thyristors,
- silicon-controlled rectifiers

100 kGy

Ionisation with electrons generates:

- electron-hole pairs
- recombination centers for minority carriers
- a variety of defects in the crystal lattice

Change of colors in gemstones by creating changes in crystalline structure

1 MGy

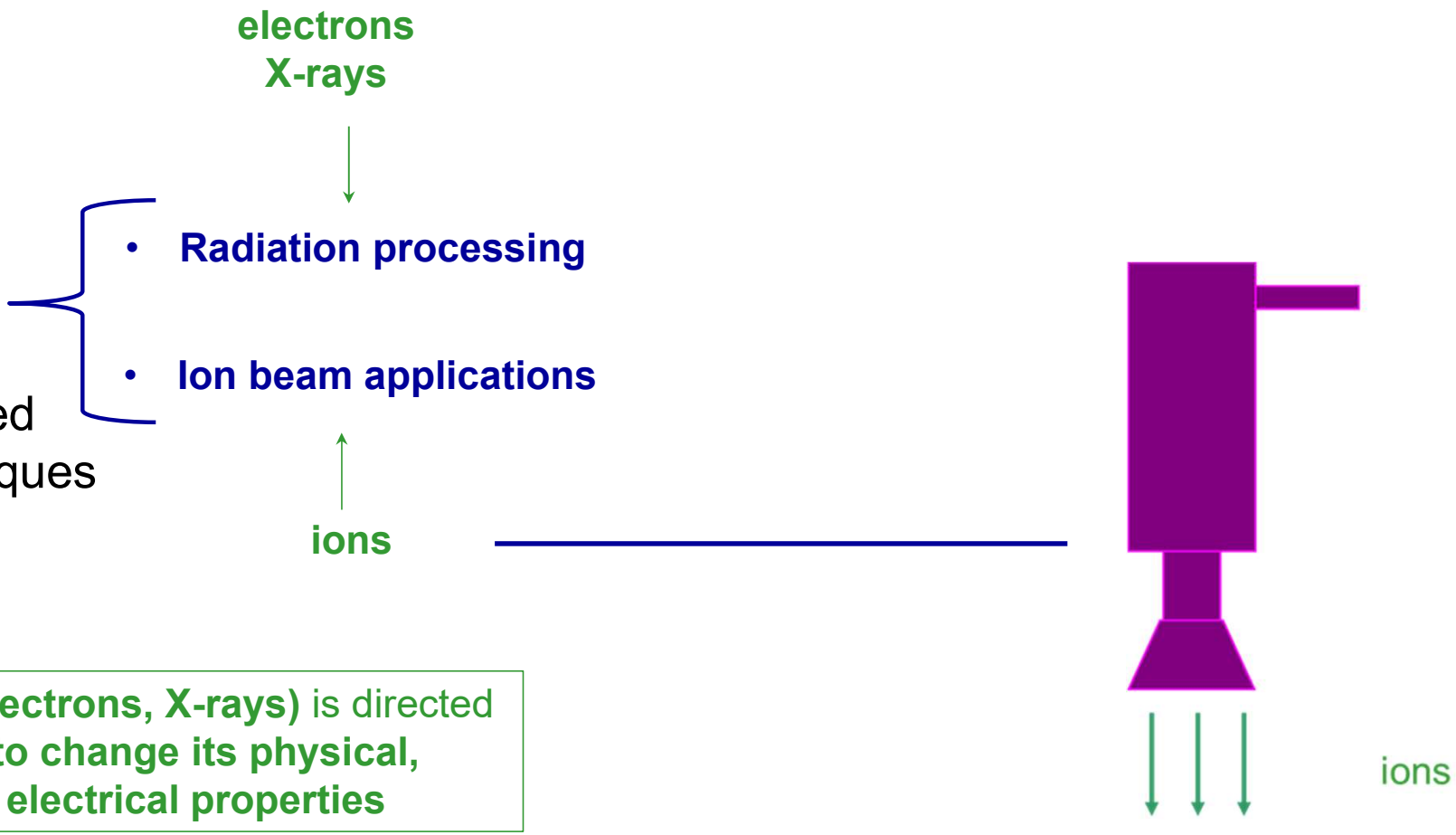
topaz

Particle Accelerators for

1. Medicine

2. Industry

3. Accelerator based analytical techniques

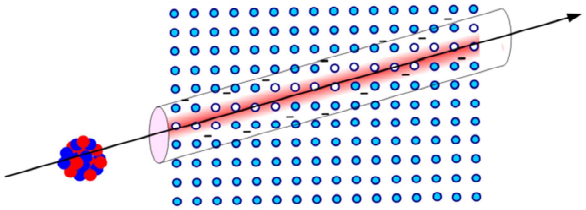


Radiation (ions, electrons, X-rays) is directed into a material **to change its physical, chemical, or electrical properties**

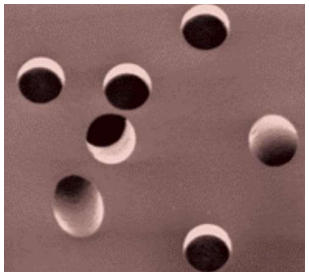
Ion beam applications

Accelerated ions are directed into a solid material, to change its physical, chemical, or electrical properties. The technique is used for:

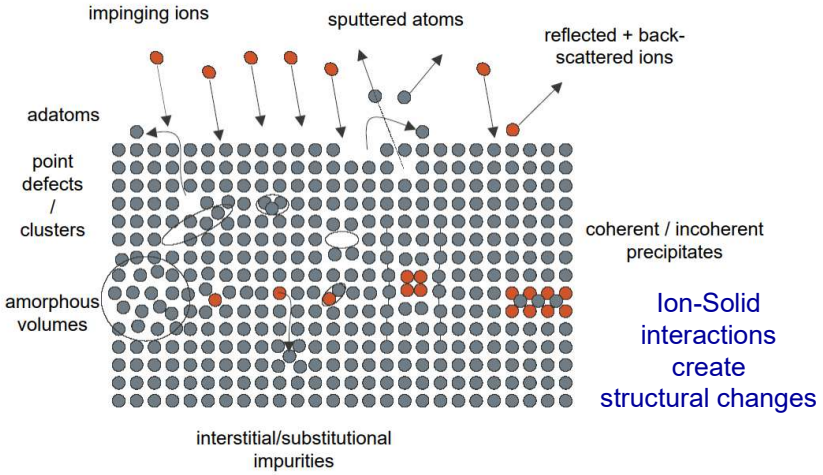
- **Nanoscale modification** of structural properties



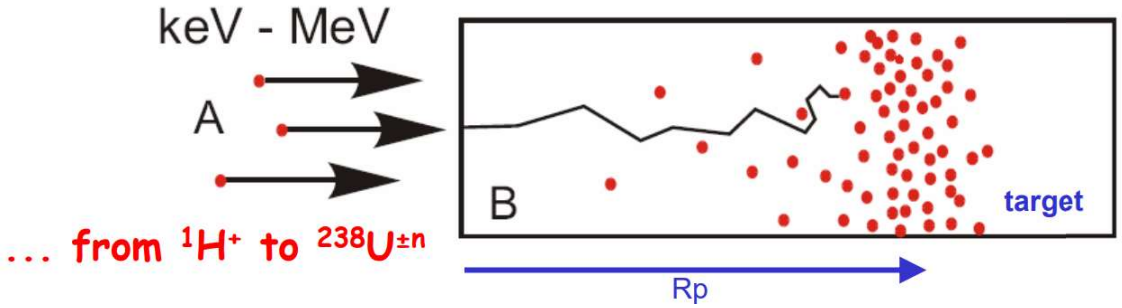
Heavy ion damage tracks in nano-structuring

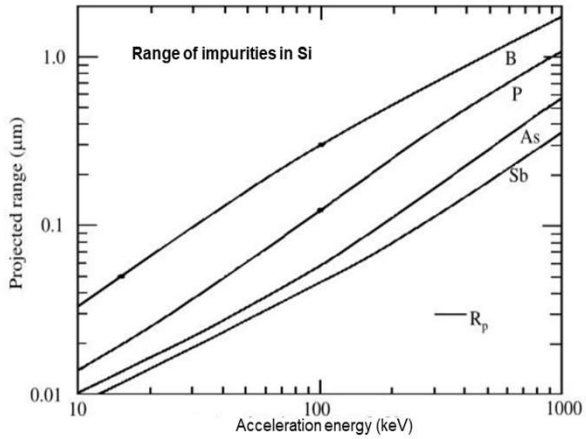


Microfiltration membranes

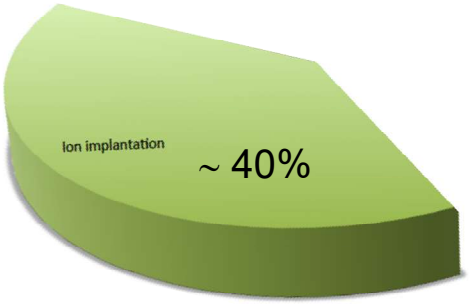


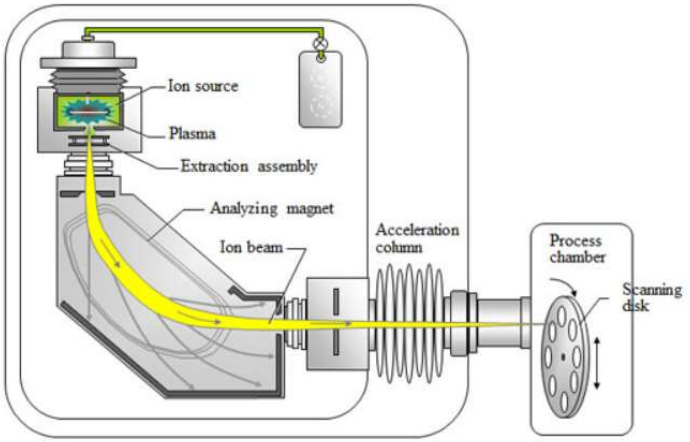
- **Ion implantation** controlled insertion of atoms into a near surface layer





Ion implantation





Semiconductor fabrication

CMOS (Complementary metal oxide semiconductor)
SIMOX (Separation by Implantation of Oxygen)
Cleaving silicon
MEMS (micro-electro-mechanical-systems)

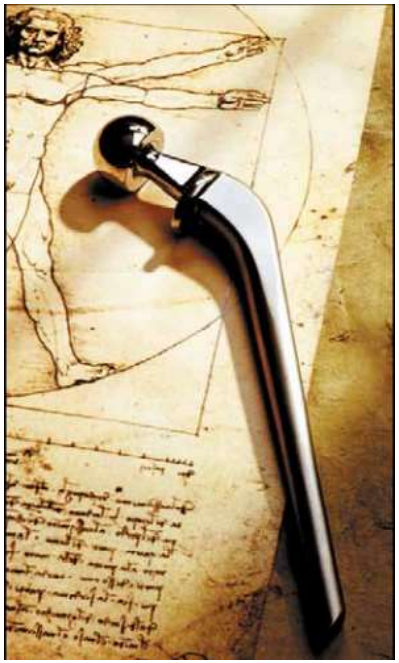
Metal finishing

Harden cutting tools
Artificial human joints

Ceramics & glasses

Harden surfaces
Modify optics

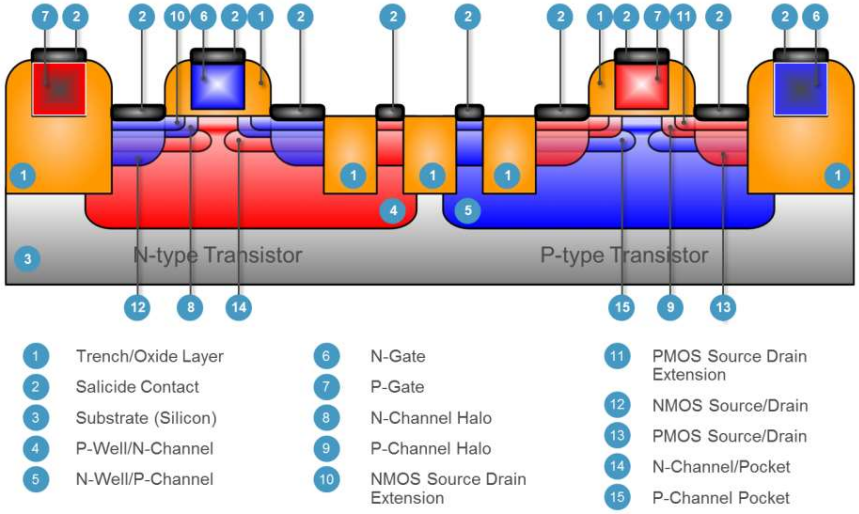
→ Nitrogen ions implanted into surgical alloys — as in this artificial femur — reduce wear and corrosion from body fluids, freeing patients from the need for repeated surgery.

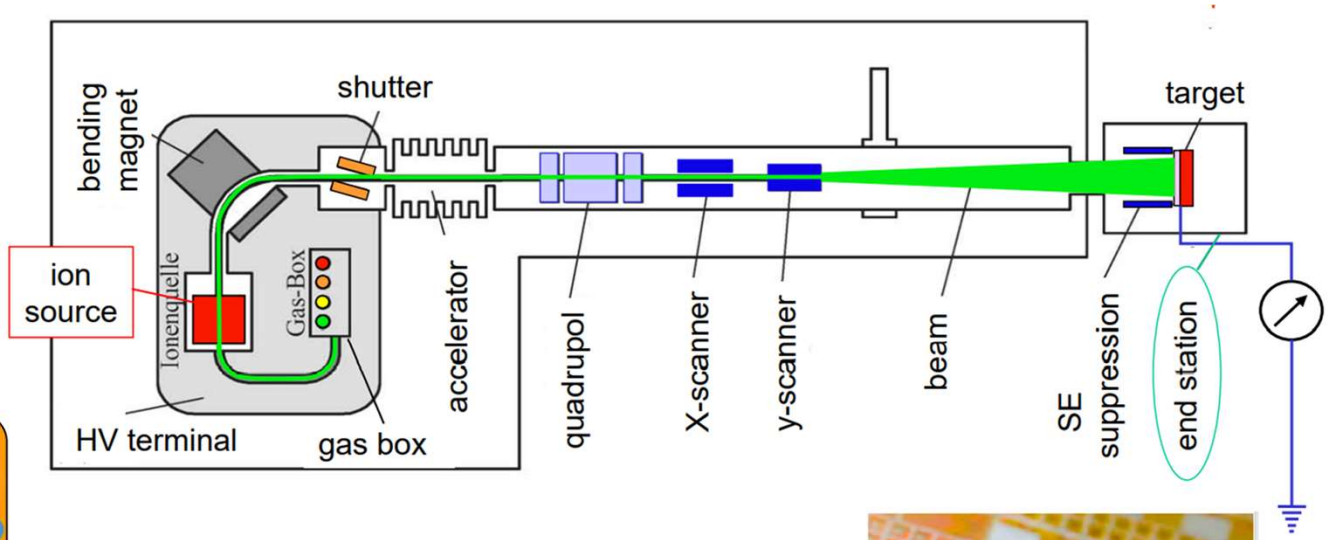


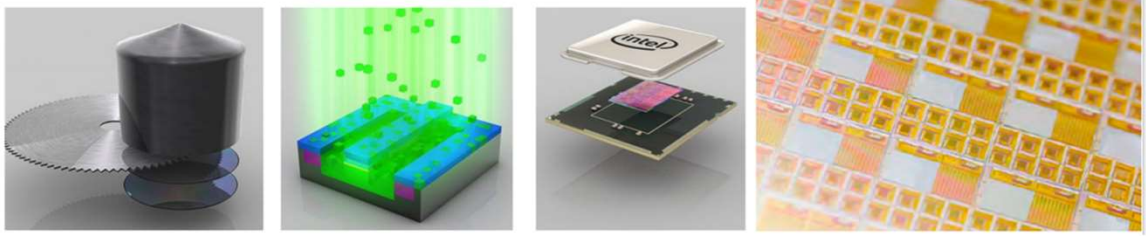
Ion implantation

doping of semiconductors

All digital electronics now highly dependent on ion implantation (B, P, As, Sb…),
95 % of all doping steps done by implantation, e.g. CMOS-IC with memory needs up to 35 implantation steps







Outline

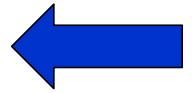
1. Introduction

2. Small accelerators for applications

3. Applications in medicine
   - radiotherapy
   - production of radioisotopes

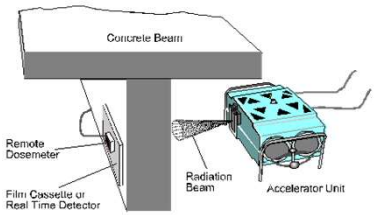
4. Applications in industry
   - radiation processing
   - ion beam applications

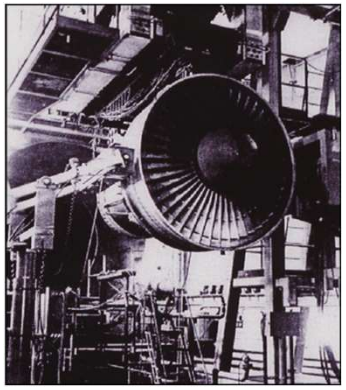
5. Analysis of physical, chemical or biological properties of materials
   - with photon or neutron beams
   - with ion beams



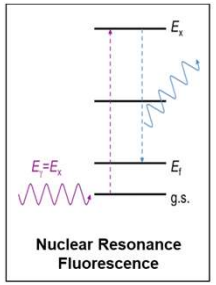
see seminar of 11 July 2023
David Cohen (ANSTO): 'Megavolt Accelerator systems for Environmental Monitoring'

Analytical techniques with photons and neutrons



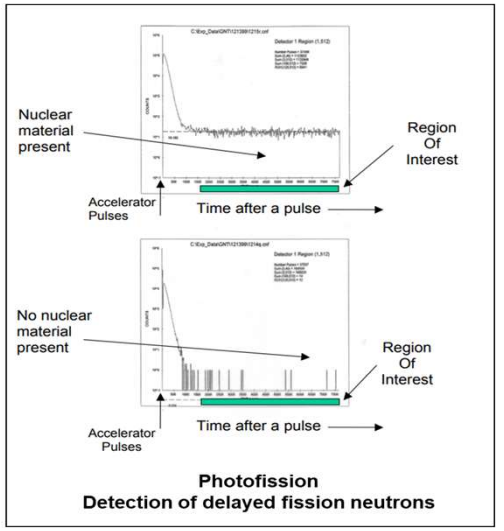


- dynamically inspecting jet engines
- X-ray screening of cargo containers
- inspecting concrete structure integrity
- inspecting castings
- reverse engineering CT studies
- nuclear waste inspection
- border control: smuggling drugs, contraband or people

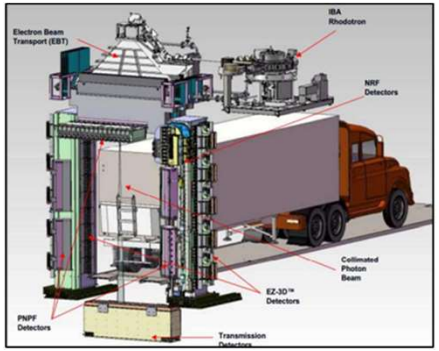


Nuclear Resonance Fluorescence

Accelerator-based active screening methods



Photofission
Detection of delayed fission neutrons



Conclusion

In the wake of the **flagships of the accelerator legion**, the well-known machines that led to so **many Nobel prizes**, **their offspring** – more than forty thousands of accelerators - are at work every day, **almost unnoticed**.

*"A beam of the **right particles** with the **right energy** at the **right intensity** can*

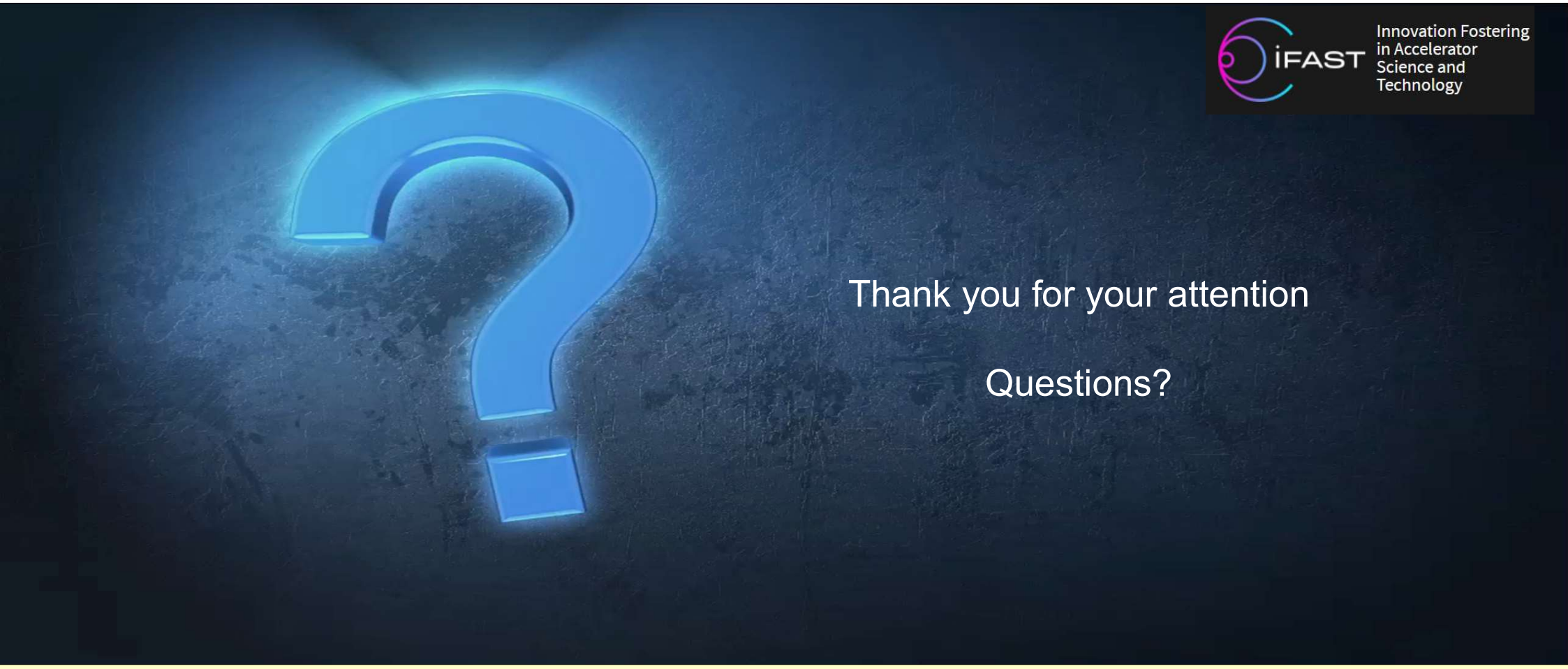
- *shrink a tumor,*
- *produce cleaner energy,*
- *spot suspicious cargo,*
- *make a better radial tire,*
- *clean up dirty drinking water,*
- *map a protein,*
- *study a nuclear explosion,*
- *design a new drug,*
- *make a heat-resistant automotive cable,*
- *diagnose a disease,*
- *reduce nuclear waste,*
- *detect an art forgery,*
- *implant ions in a semiconductor,*
- *prospect for oil,*
- *date an archaeological find,*
- *package a turkey or…*

… discover the secrets of the universe."

Quote from 'Accelerators for Americas Future' Report, pp. 4, DoE, USA, 2011

iFAST Innovation Fostering in Accelerator Science and Technology

Europe's future



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