LOW-ENERGY ELECTRON ACCELERATORS

Applications in medicine and industry PART 1

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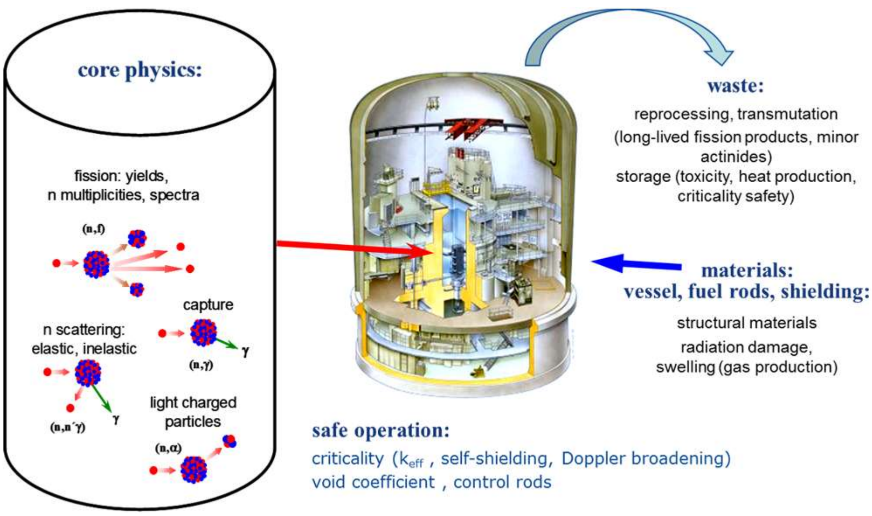
Ghent University
and
Joint Research Centre
the European Commission's
in-house science service

1

Unit Standards for nuclear safety, security and safeguards

EURATOM Research Programme

Nuclear Data for safety of present-day and innovative nuclear energy systems



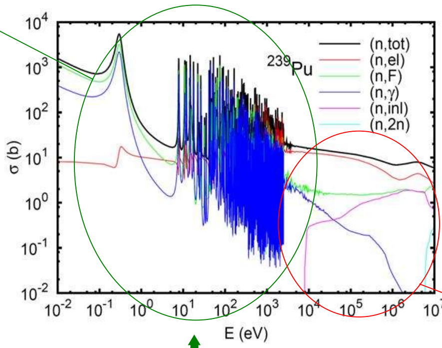
safe operation:
criticality (k_{eff}, self-shielding, Doppler broadening)
void coefficient , control rods

2

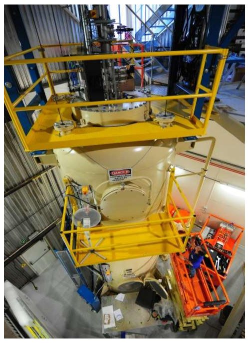
2

GELINA and MONNET: nuclear data research

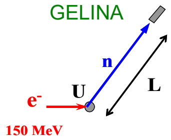
Time-of-flight measurements



MONNET

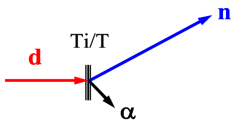


GELINA

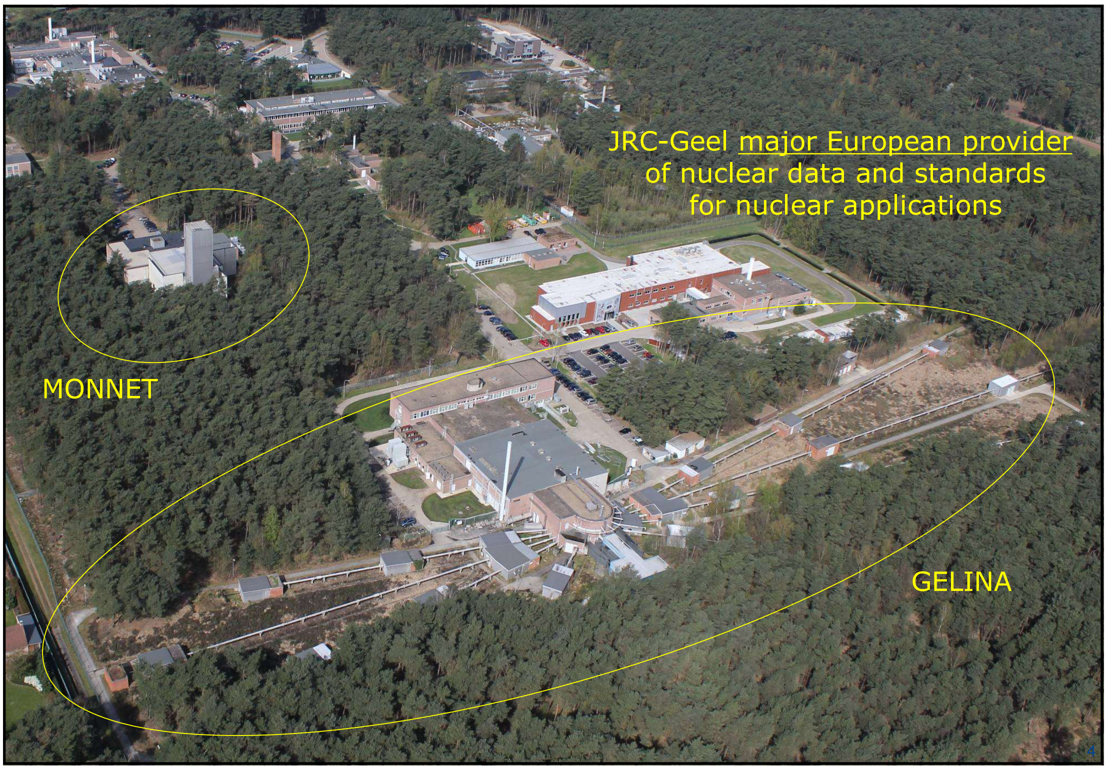


energy resolution

Mono-energetic neutron beams



$$E = \frac{1}{2} m v^2 \propto \left(\frac{L}{T}\right)^2$$



Department of Physics and Astronomy
GHENT UNIVERSITY

15 MeV electron accelerator

intense electron and X-ray beams

radiation physics

biomaterials research

polymer chemistry

atomic and solid-state physics

medicine

food technology and agriculture

Nuclear Research

↓

Multidisciplinary Research

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Accelerators in the world *

year 2007

(approximate numbers)

APPLICATION	
High-energy physics research	120
Synchrotron radiation sources	50
Ion beam analysis	200
Photon or electron therapy	9100
Hadron therapy	30
Radioisotope production	550
Ion implantation	9500
Neutrons for industry or security	1000
Radiation processing	2000
Electron cutting and welding	4500
Non-destructive testing	650
TOTAL	27700

* R. Hamm
at 9th ICFA Seminar
October 30, 2008

~ 60% low-energy electron accelerators

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Low-energy electron accelerators

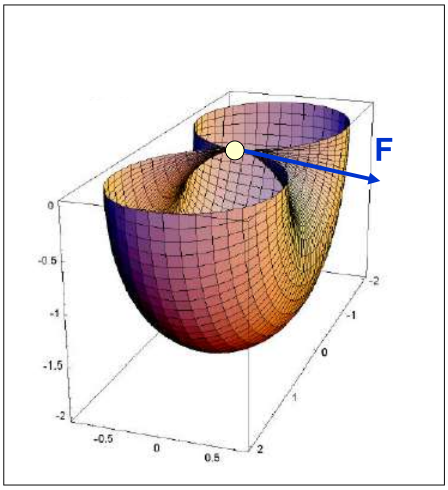
X-rays | electrons

1. Basic principles of X-ray production
   → *bremsstrahlung*
   → *synchrotron radiation*
2. Physical, chemical and biological aspects of the application of electrons and bremsstrahlung photons
3. Electron accelerators in medicine
4. Electron accelerators in industry
5. Electron storage rings for medicine and industry

Radiation of a <u>non-relativistic</u> accelerating charge

LARMOR

$$P = \frac{q^2}{6\pi\varepsilon_0 m_o^2 c^3}\left(\frac{d\vec{p}}{dt}\right)^2$$



Radiated power ~ $1/m_0^2$

→ protons - electrons: factor 3.5 10^6

Radiation of a relativistic accelerating charge

LIENARD

$$P = \frac{q^2\gamma^6}{6\pi\varepsilon_0 c^3}\left[\left(\frac{d\vec{v}}{dt}\right)^2 - \frac{1}{c^2}\left(\vec{v}\wedge\frac{d\vec{v}}{dt}\right)^2\right]$$

Longitudinal force

$$\frac{d\vec{v}}{dt} = \frac{1}{m_0\gamma^3}\frac{d\vec{p}}{dt} \longrightarrow P = \frac{q^2}{6\pi\varepsilon_0 m_o^2 c^3}\left(\frac{d\vec{p}}{dt}\right)^2$$

Transversal force

$$\frac{d\vec{v}}{dt} = \frac{1}{m_0\gamma}\frac{d\vec{p}}{dt} \longrightarrow P = \frac{q^2\gamma^2}{6\pi\varepsilon_0 m_o^2 c^3}\left(\frac{d\vec{p}}{dt}\right)^2$$

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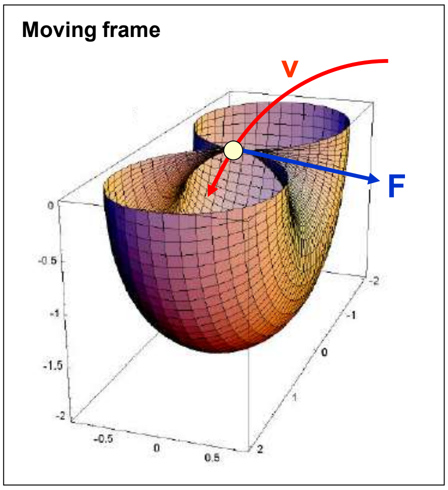
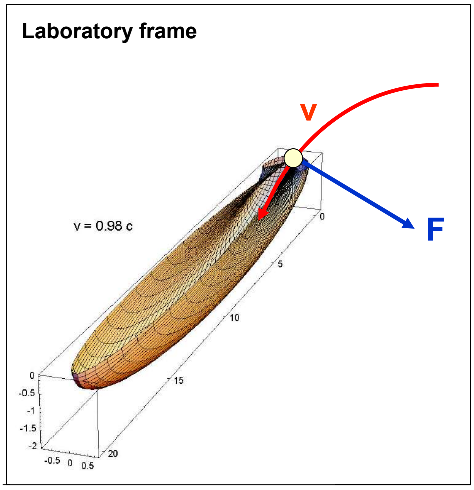
Radiation of an accelerating charge - angular distribution





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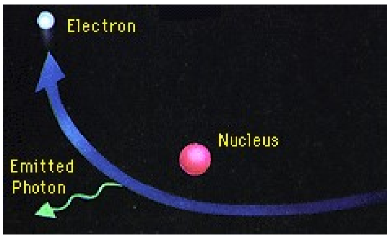
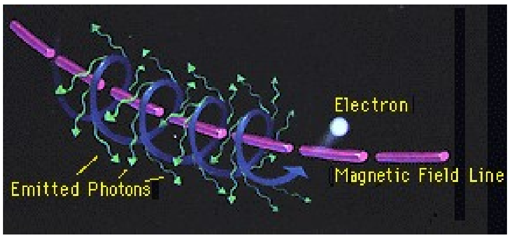
Radiation of relativistic electrons in a transverse field

Coulomb field of atomic nuclei



Magnetic field

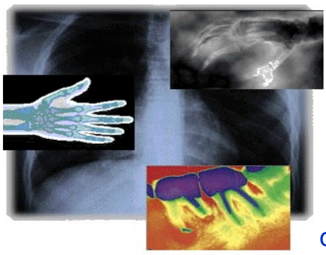


BREMSSTRAHLUNG

braking radiation

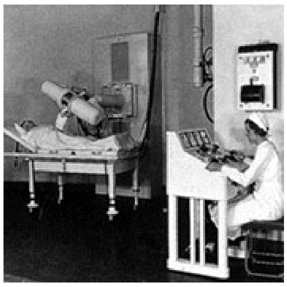
SYNCHROTRON RADIATION

Low-energy electron accelerators in medicine



1895 Röntgen
discovery of X-rays

1896 Becquerel
discovery of radioactivity



diagnosis → X-ray radiography

treatment → X-ray radiotherapy

↓

Radioactive sources

skin-sparing ↑
side scatter ↓
depth-dose ↑

← Accelerator-based radiotherapy

Accelerator-based radiotherapy

1937 first hospital-based VAN DE GRAAFF

1946 first hospital-based BETATRON

1952 first hospital-based RF LINAC

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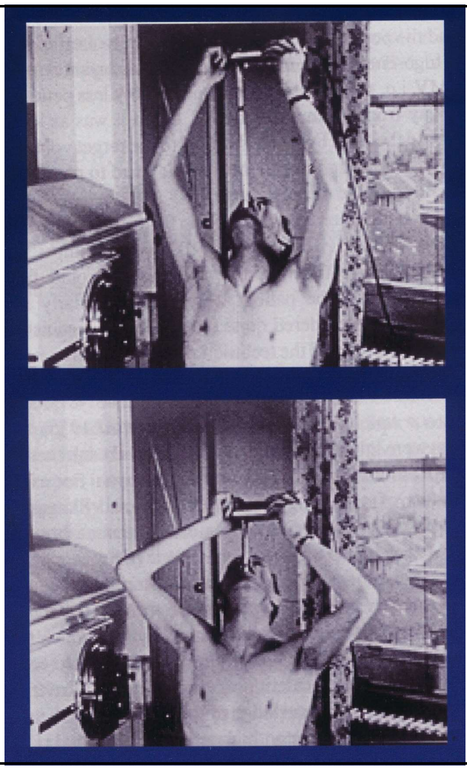
1953



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Accelerator-based radiotherapy

1937 first hospital-based VAN DE GRAAFF

1946 first hospital-based BETATRON + WILSON: use of protons and ions

1952 first hospital-based RF LINAC

1990 first hospital-based PROTON SYNCHROTRON

Now electrons and photons: routine therapy
⇓
IMRT, IGRT, IMAT, CYBERKNIFE…

protons and ions remains less conventional

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Low-energy electron accelerators in industry

1905 APPLEBY and MILLER, patent:
'use of X-rays to bring about an improvement in the conditions of foodstuffs'

1956 JOHNSON and JOHNSON
sterilisation of medical devices

INDUSTRY	radiation processing
in a car:	dashboard, tyres, cables, painting ...
in an airplane:	constructional components …
at the doctor:	syringes, pharmaceuticals, sterile dressings ….
in the supermarket:	strawberries, red meat, shrink packaging materials …
in the clothing shop:	permanently-creased trousers or T-shirts, raincoats …
at home:	electrical cables, parquet ….
in the human body:	prostheses, catheters, advanced drug-delivery systems ...

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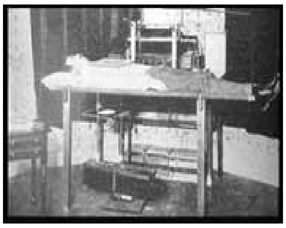
Why has it taken so long ?

MEDICINE

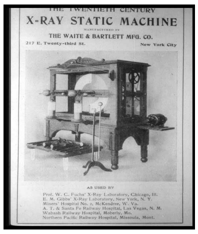


80 years ↓

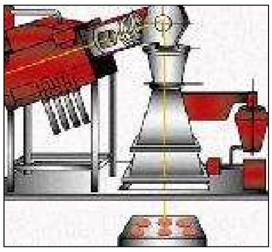
Beam energy
power
quality
↔ compact
reliable
simple
\+ economics

beam power ↑↑↑

INDUSTRY



↓ 100 years



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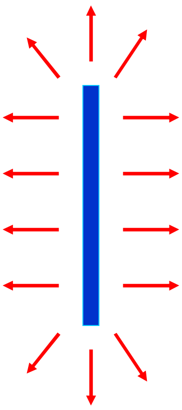
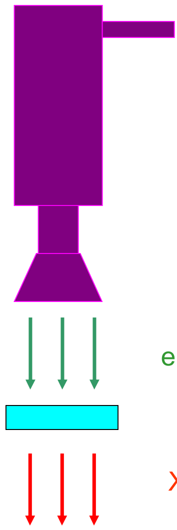
γ - rays



^{60}Co	5.2 years 1.173 MeV, 1.333 MeV 14.8 kW / MCi
^{137}Cs	30.2 years 0.622 MeV 3.3 kW / MCi

electrons **X - rays**



5 MeV photons
10 MeV electrons

Nuclear reactions
Activation

7.5 MeV photons

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Bremsstrahlung production

COLLISION STOPPING POWER → HEAT !!!

$$-\left(\frac{dT}{dx}\right)_c = 2\pi\frac{e^4NZ}{m_e\beta^2c^2}\left[\ln\frac{m_e\beta^2c^2T}{2I^2(1-\beta^2)}+(1-\beta^2)-\ln 2(2\sqrt{1-\beta^2}-1+\beta^2)+\frac{\left[1-\sqrt{1-\beta^2}\right]}{8}\right]$$

BREMSSTRAHLUNG STOPPING POWER

$$-\left(\frac{dT}{dx}\right)_r = \frac{NTZ(Z+1)e^4}{137m_e^2c^4}\left[4\ln\left(\frac{2T}{m_ec^2}\right)-\frac{4}{3}\right]$$

high Z
high melting point
< 5 MeV

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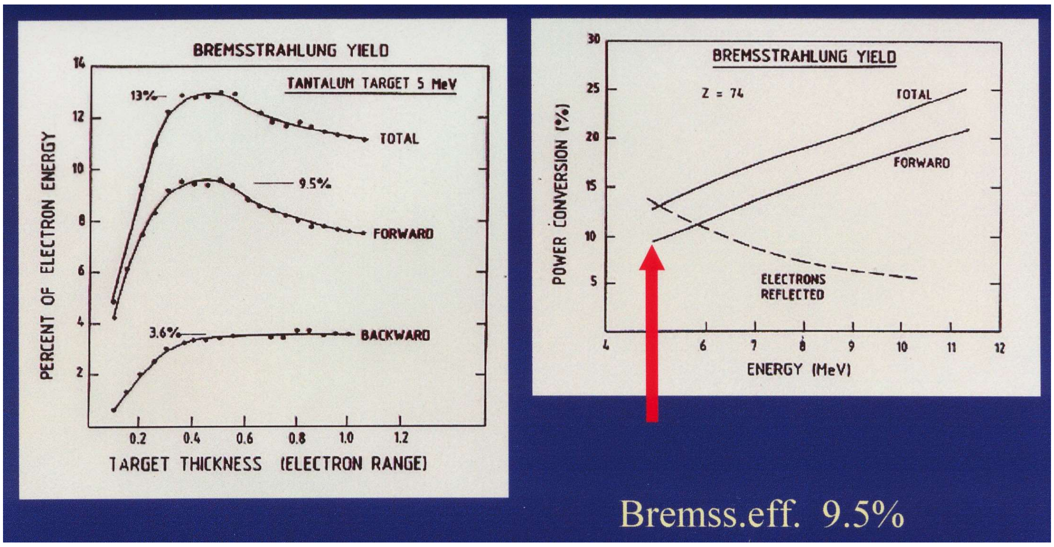

1 MCi of ^{60}Co ↔ 5 MeV / 155 kW

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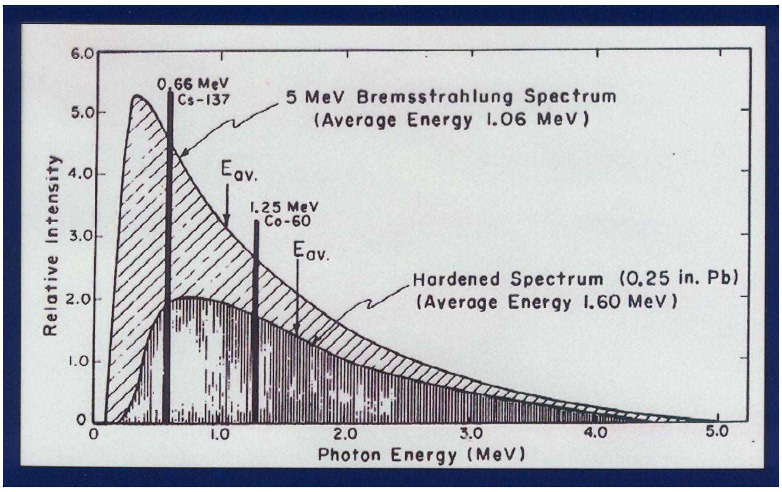


BREMSSTRAHLUNG SOURCE:

- forward-peaked
- on / off
- Cobalt 12.4% / year ↓
- no nuclear waste
- X-ray and electron mode

Low-energy electron machines

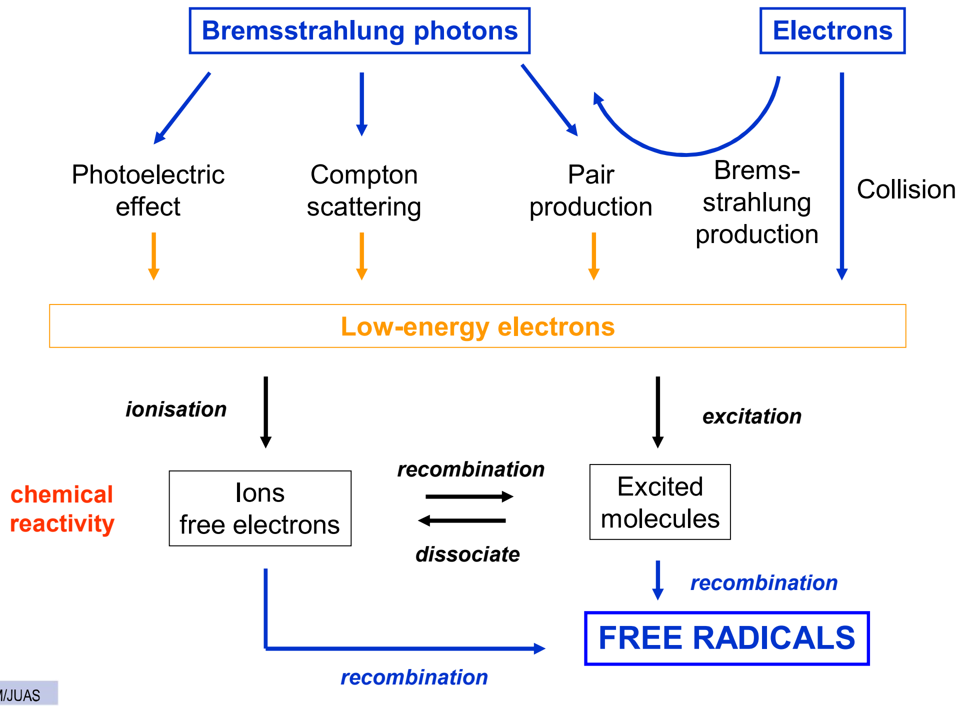
1. Basic principles of X-ray production
   → *bremsstrahlung*
   → *synchrotron radiation*

2. Physical, chemical and biological aspects of the application of electrons and bremsstrahlung photons

3. Electron accelerators in medicine

4. Electron accelerators in industry

5. Electron storage rings for medicine and industry



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FREE RADICALS

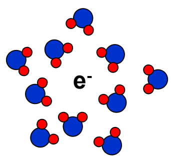
→ Molecules, ions or atoms with an unpaired electron in the outer shell

RADIOLYSIS OF WATER

H_2O	→	$H_2O^+ + e^-$
$H_2O + e^-$	→	H_2O^-
$H_2O^+ + H_2O^-$	→	$H^+ + OH^- + H° + OH°$

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

$H° + OH°$	→	H_2O
$H° + H°$	→	H_2
$OH° + OH°$	→	H_2O_2



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FREE RADICALS

↓

- **damage DNA** — ***radiotherapy***, ***food irradiation***, ***sterilisation***
- **chain reaction**
  R° + AB → R- AB°
  R- AB° + AB → R- AB-AB°
  polymer chemistry
- **special chemical reactions** — ***radiation synthesis***
- **graft a second polymer** — ***curing***, ***biomaterials***

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Physical, chemical and biological effects
~ deposited energy

↓

DOSE = deposited energy per unit mass

1 Gray = 1 J / kg

1 Gy = 100 rad

4.2 kGy in water → 1° C

⇒ high yields of reactive species at low temperatures

ELECTRONS or PHOTONS
similar end products
different spatial distributions

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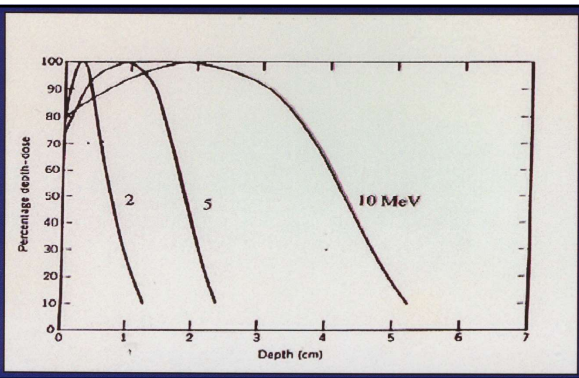
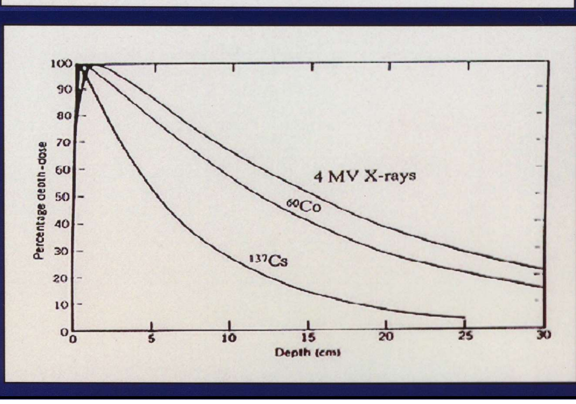
ELECTRONS



Single-sided irradiation

PHOTONS



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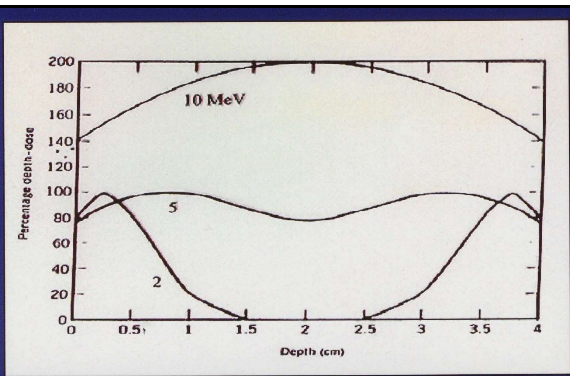
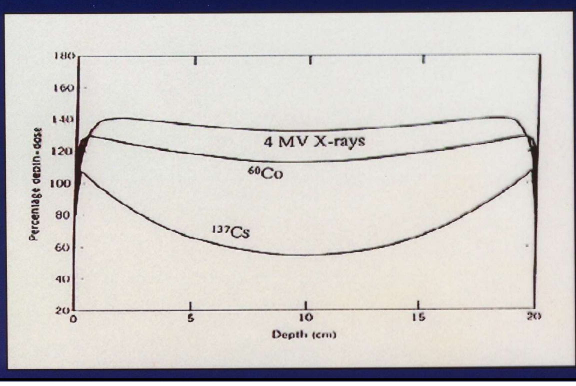
ELECTRONS



Double-sided irradiation

PHOTONS



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PATIENT

Initial physical, chemical and biological properties

MATERIAL

↓ **RADIATION**

TREATED PATIENT

Altered physical, chemical and biological properties

PROCESSED MATERIAL

↓

Quality of life ↑
% survival ↑

↓

Quality ↑
new features

!!! Minimum of side effects !!!

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Low-energy electron machines

1. Basic principles of X-ray production
   → *bremsstrahlung*
   → *synchrotron radiation*

2. Physical, chemical and biological aspects of the application of electrons and bremsstrahlung photons

→ 3. Electron accelerators in medicine **Gy - range**

4. Electron accelerators in industry **kGy - range**

5. Electron storage rings for medicine and industry

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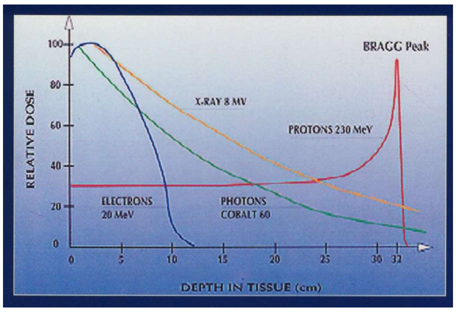
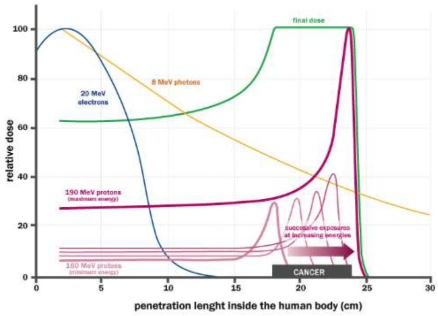
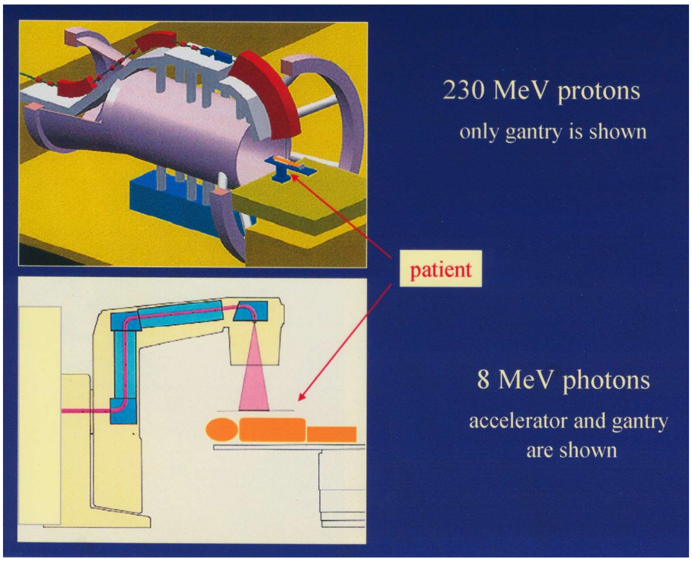
Why X-rays or electrons ?

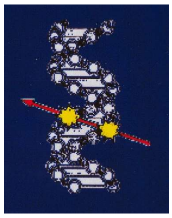


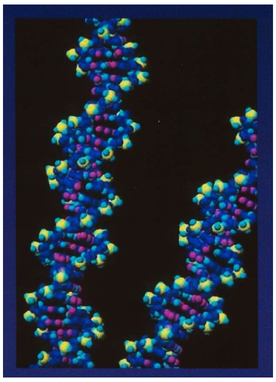


Protons versus X-rays ?

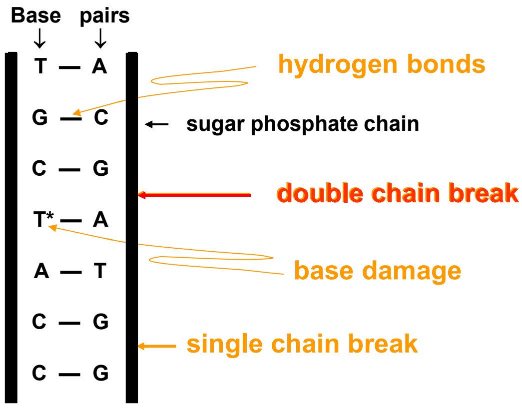


Photons and electrons in radiotherapy





Radiation damage to DNA:
- direct
- indirect by free radicals and reactive species



Repair mechanisms

60 Gy survival probability
10^{-9}

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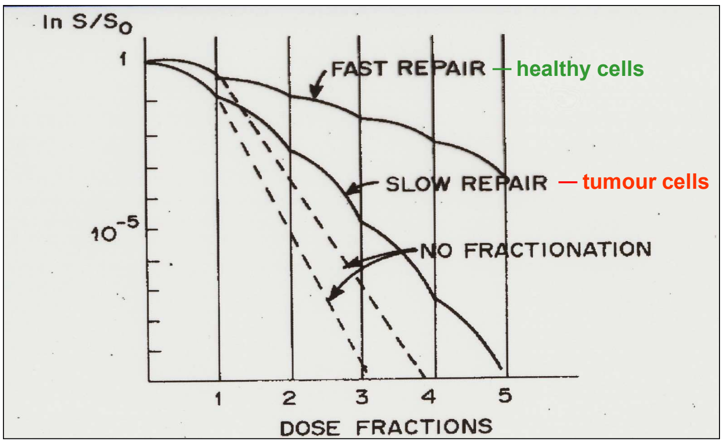
Dose fractionation

- dose-dependent survival fraction
- oxygenation
- radiosensitivity during cell cycle



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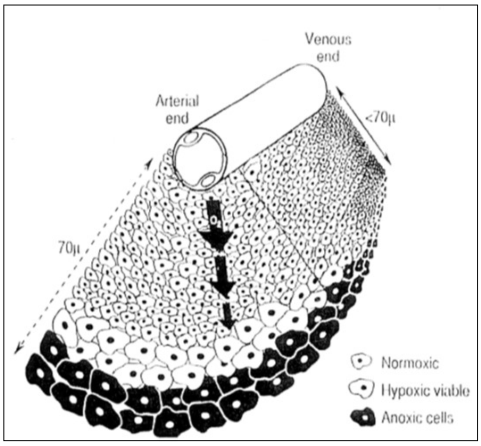
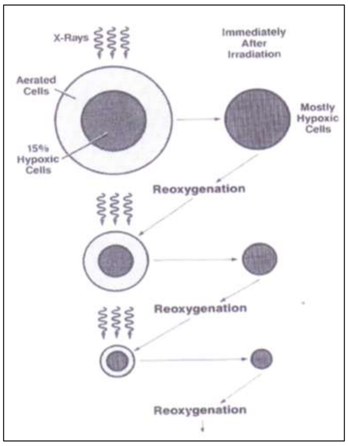
Dose fractionation

- dose-dependent survival fraction
- oxygenation
- radiosensitivity during cell cycle



Cells are more anoxic further from blood vessels



Tumour shrinks

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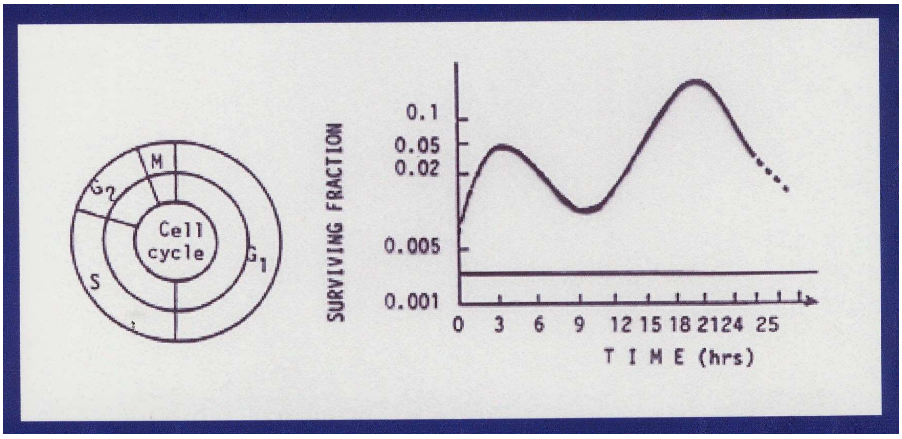
Dose fractionation

- dose-dependent survival fraction
- oxygenation
- radiosensitivity during cell cycle



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Radiotherapy

30 fractions of 2 Gy

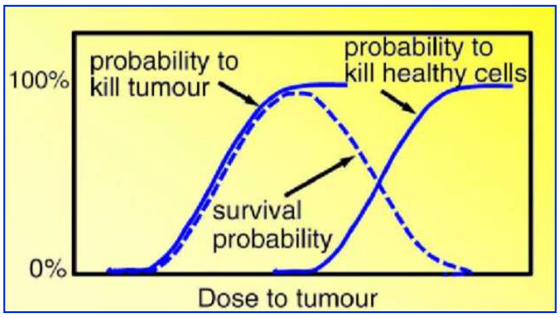
4 Gy / min

40 x 40 cm^2

⇩

Very high accuracy
of dose delivery

Treatment dose
PLANNING
DELIVERY



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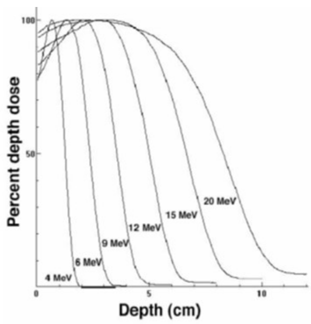
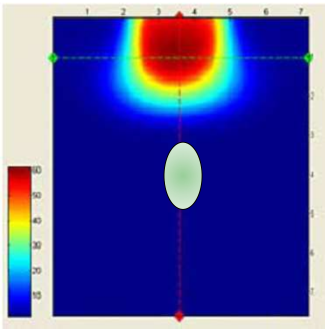
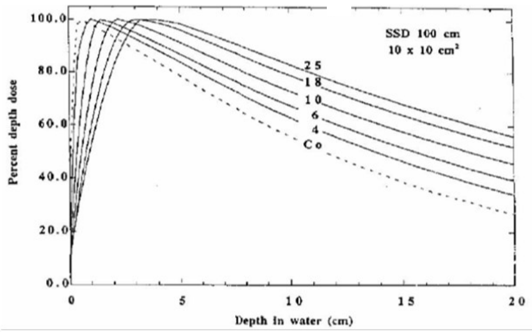
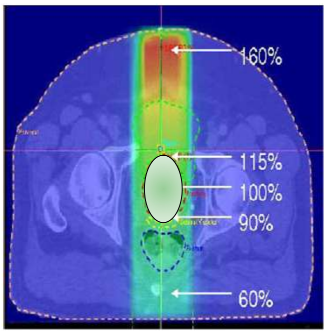
electrons





photons





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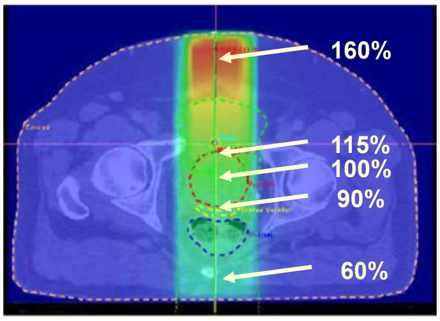
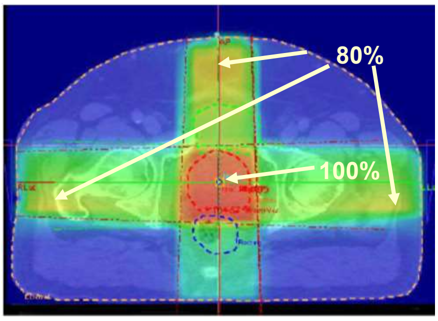
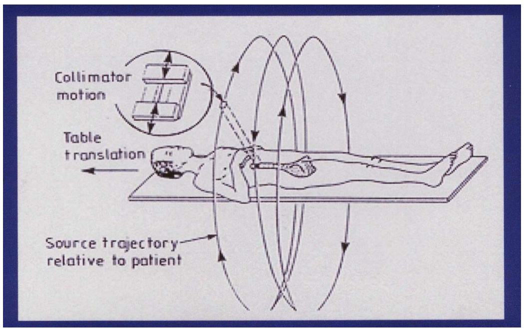


SINGLE BEAM



MORE BEAMS

Multiple beams



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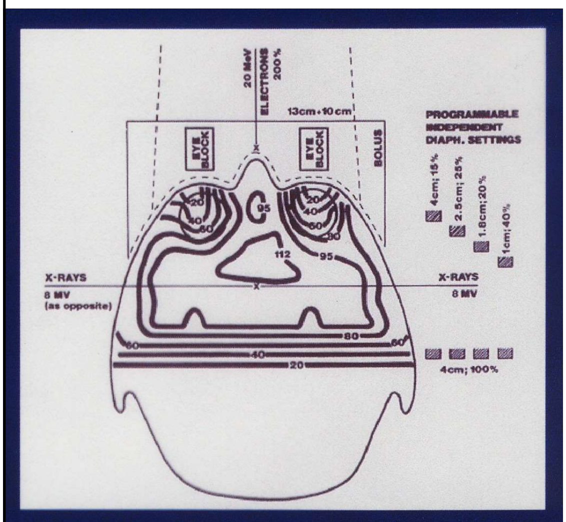
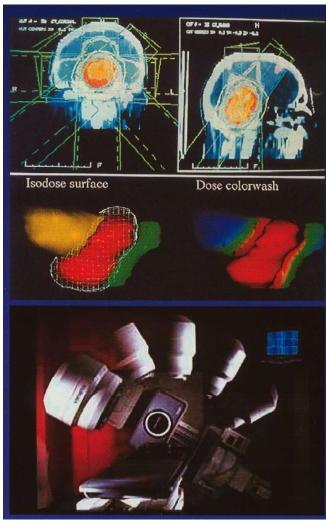
Combination of rectangular uniform radiation fields





Treatment dose planning

Treatment dose delivery

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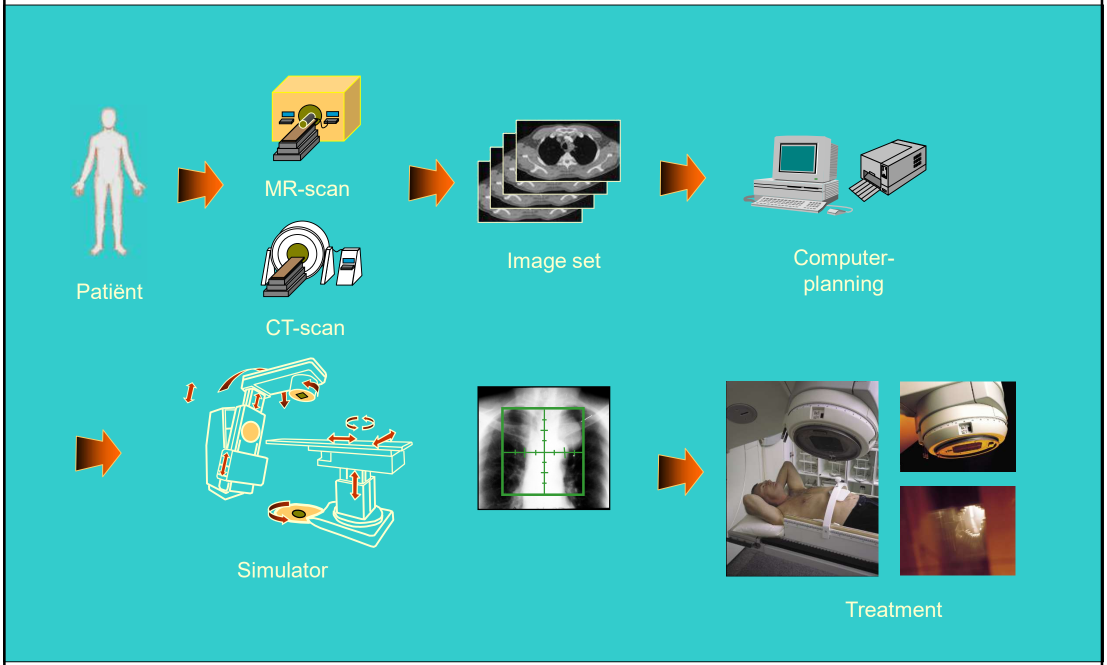
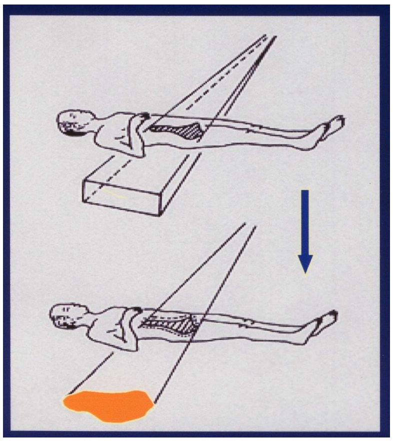
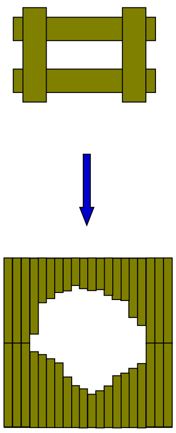


Conformal therapy : irregular-shaped uniform radiation fields





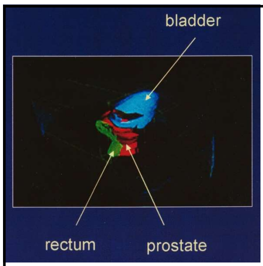
3-D imaging

3-D dose planning

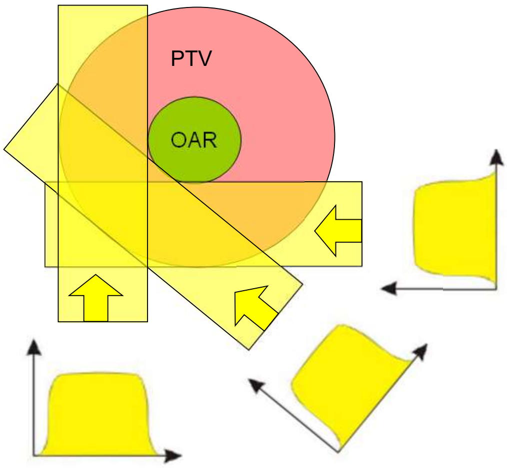
accelerator technology

dose monitoring

patient positioning



Intensity-Modulated RadioTherapy: IMRT



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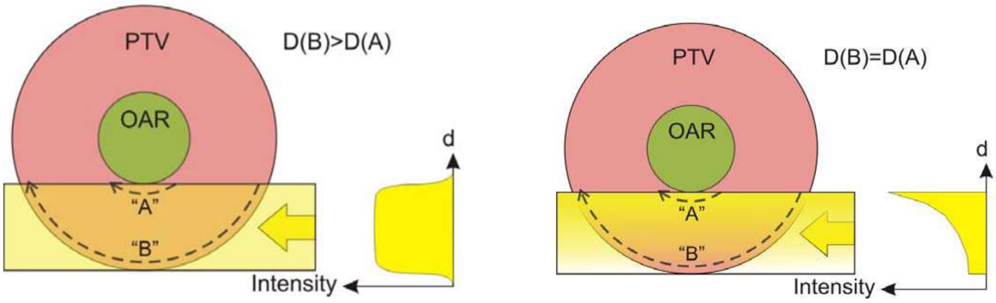
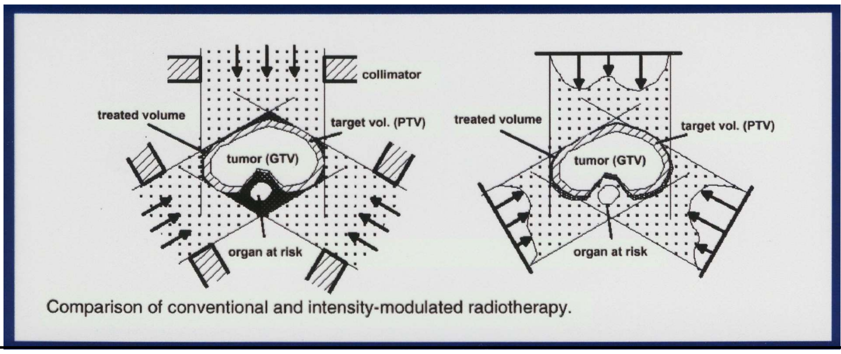
IMRT





Comparison of conventional and intensity-modulated radiotherapy.

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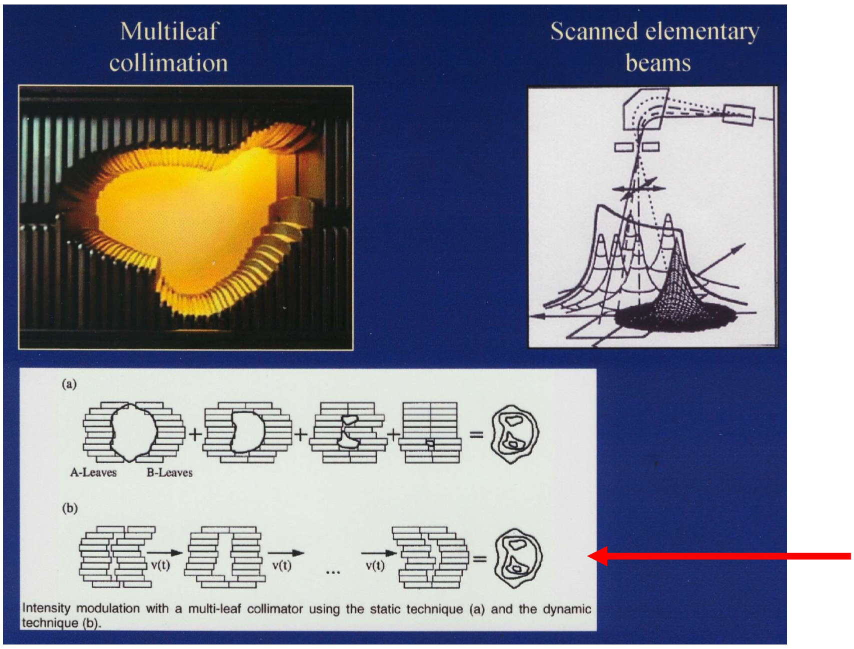
IMRT



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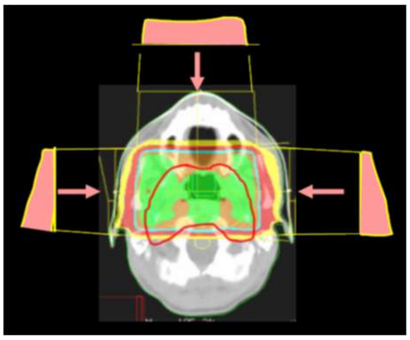
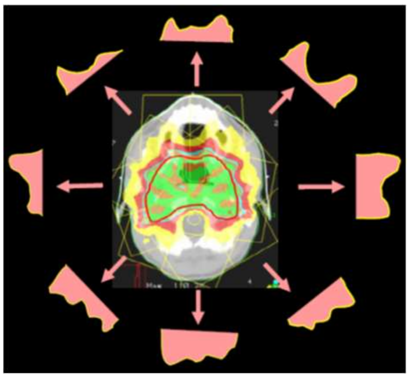


Forward treatment planning



Inversed treatment planning

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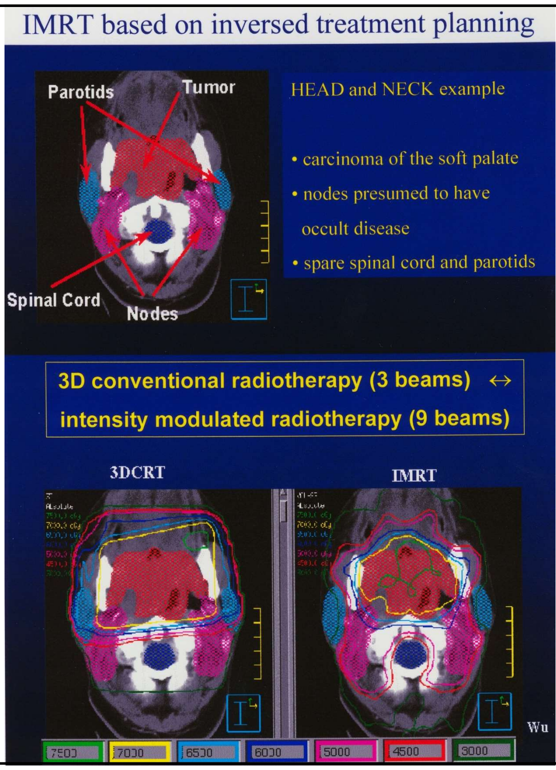

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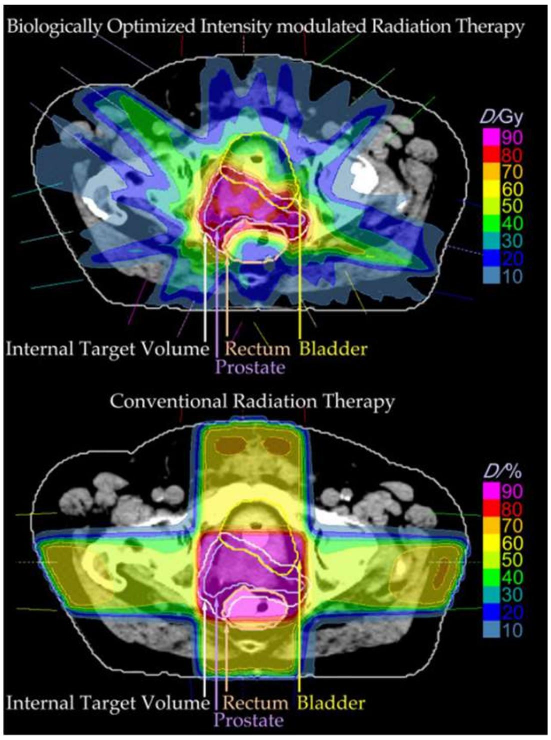

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