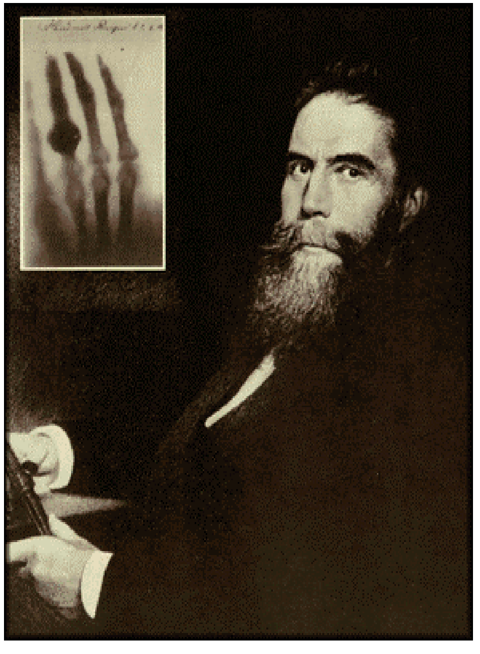
Designing a treatment beam (Beam shaping)

DISCOVERY OF X-RAYS BY RÖNTGEN

8 November 1895: Röntgen noticed an extraordinary glow while investigating the behavior of light outside a cathode tube. To his astonishment, he saw the shadows of the bones of his hand when held between the tube and a fluorescent screen.




EINE NEUE ART
VON
STRAHLEN.

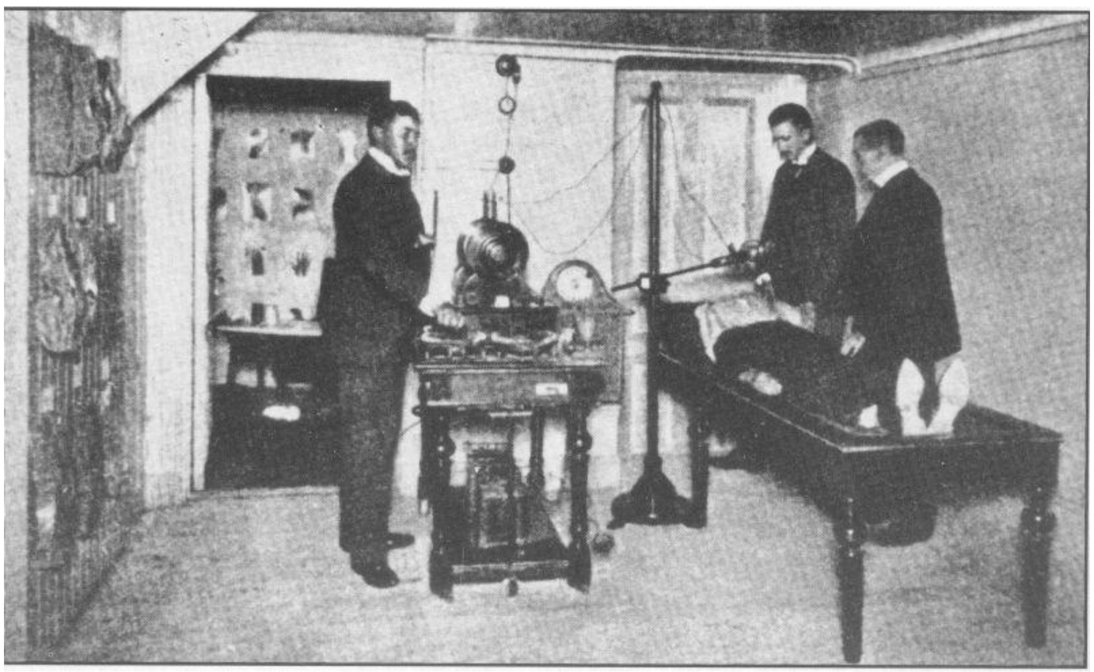
II. Mittheilung.

Von

DR. WILHELM KONRAD RÖNTGEN
O. Ö. PROFESSOR AN DER K. UNIVERSITÄT WÜRZBURG.

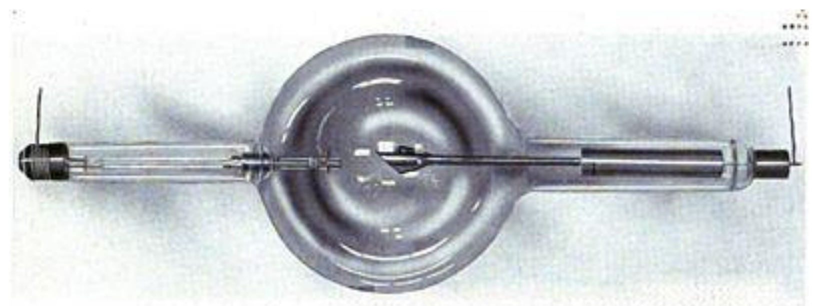
FIRST CURATIVE RADIOTHERAPY WITH X-RAYS

In 1899, in Stockholm, Thor Stenbeck initiated the treatment of a 49-year-old woman's basal-cell carcinoma of the skin of the nose, delivering over 100 treatments in the course of 9 months. The patient was living and well 30 years later.



THE COOLIDGE X-RAY TUBE

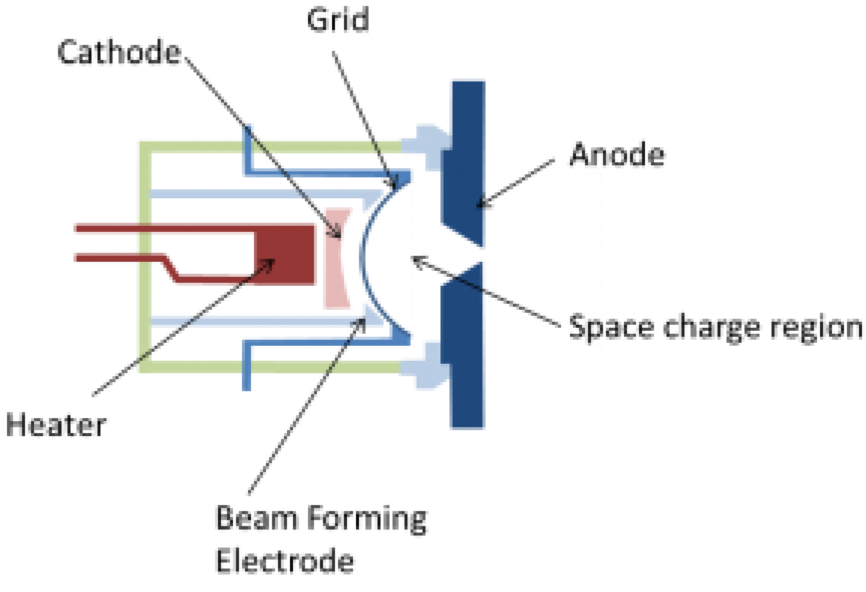
1913: William Coolidge developed the "hot" cathode tube. The tube provided a reliable beam with improved hardness and penetration, and eliminated the guesswork of "gas" tubes. The Coolidge tubes also made possible the development of orthovoltage kV X-ray therapy.



Coolidge X-ray tube, from early 1900s. The heated cathode is on the left, and the anode is right. The X-rays are emitted downwards.

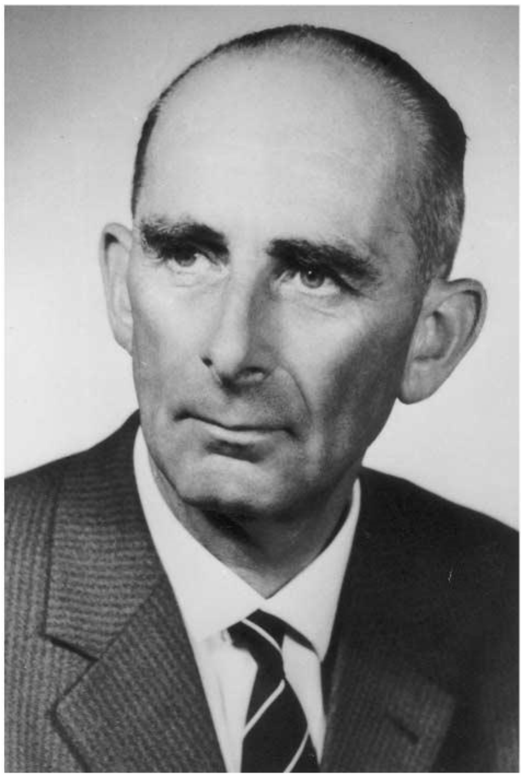
LINAC GUN IS VERY SIMILAR TO HOT CATHODE

Cathode: a piece of metal which, when heated, gives off electrons
Anode: electrons are then accelerated by a positively charged electrode
Grid: Controls the intensity of the electron beam entering the anode.



INVENTION OF LINEAR ACCELERATORS

1928: Developed by Rolf Wideröe, a Norwegian physicist working for the Brown-Boveri Company of Switzerland



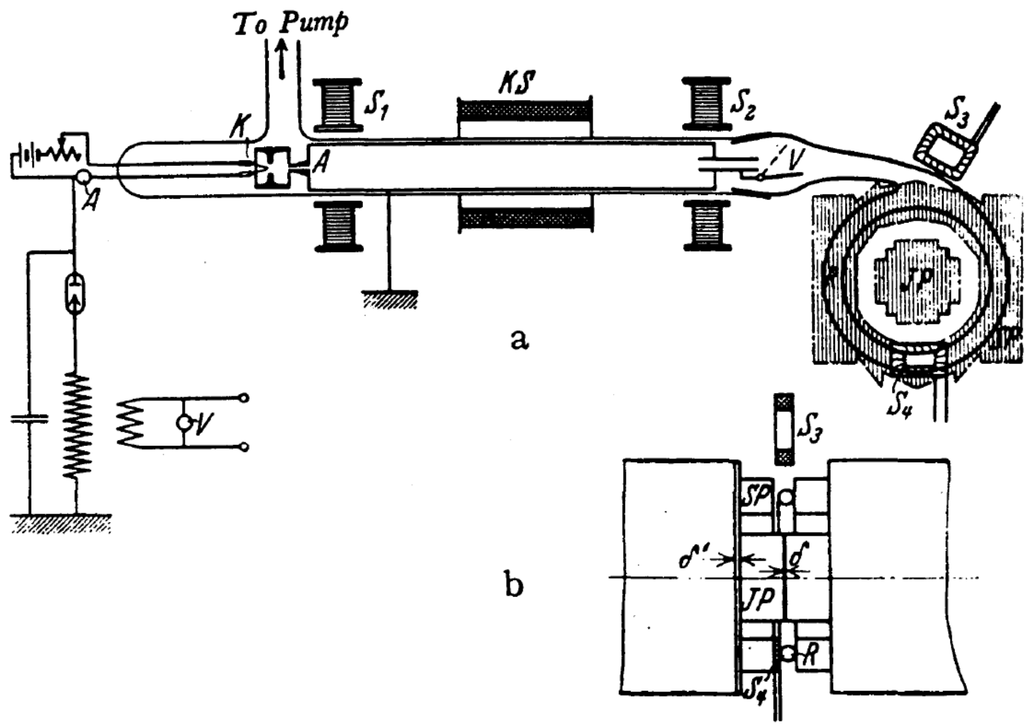
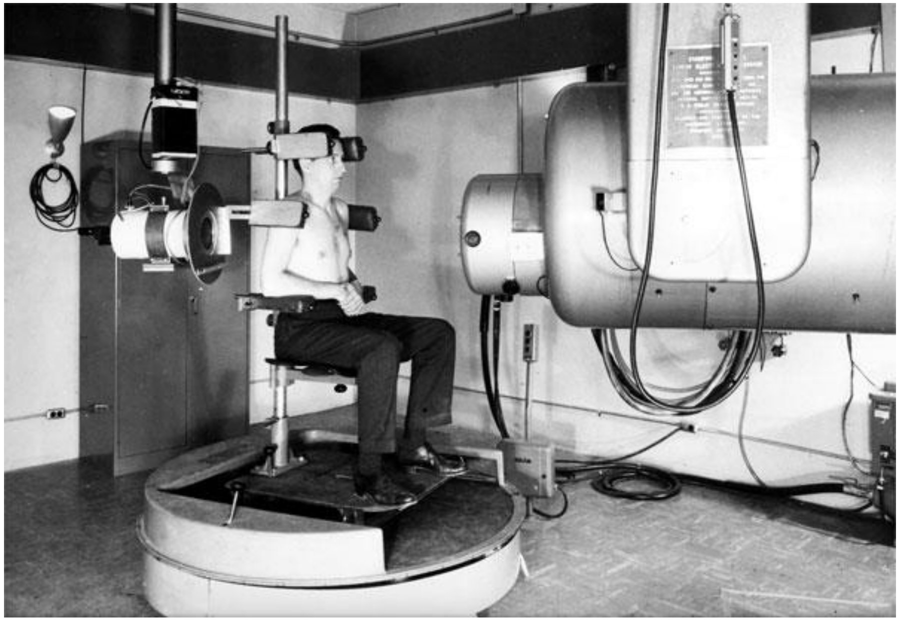


Figure 2. The Hot-cathode Electron Tube (a) and the Transformer Poles (b).

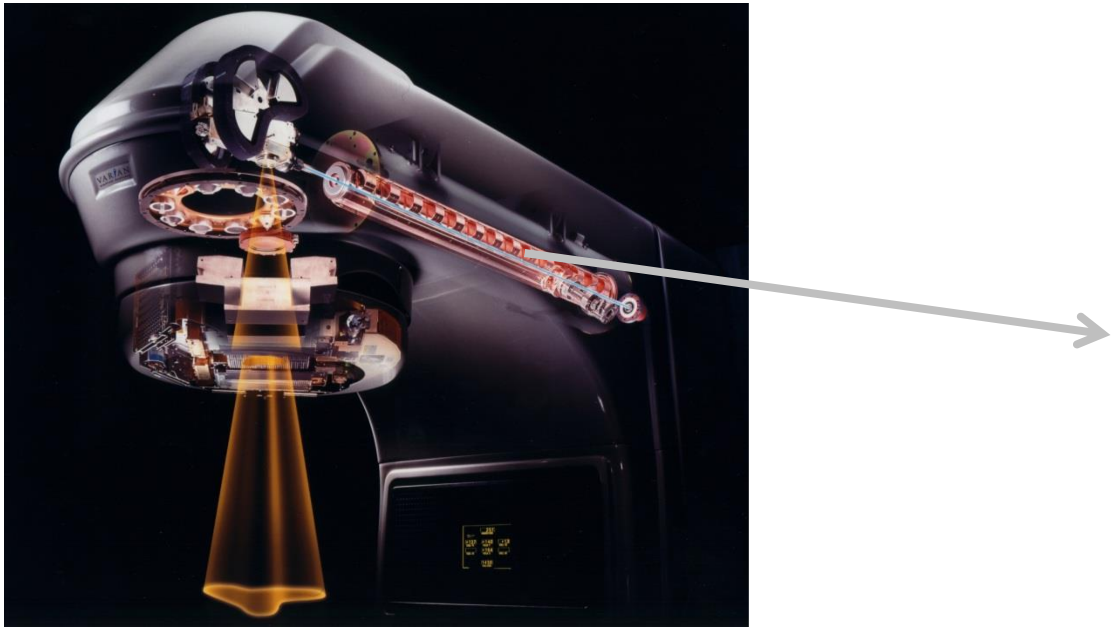
INVENTION OF LINEAR ACCELERATORS

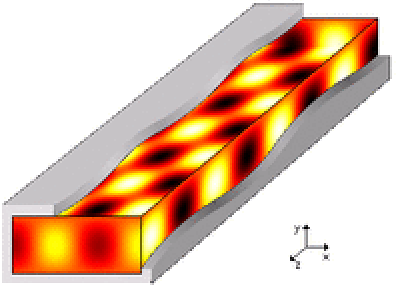
1956: This little boy was the first patient treated with the linear accelerator at Stanford Medical Center. The patient had lost one eye to retinoblastoma, but treatment saved the other



WAVEGUIDE: ACCELERATION OF ELECTRONS

Waves propagate in all directions in open space as spherical waves. The power of the wave falls with the distance from the source as inverse square law. A waveguide confines the wave to propagate in one dimension, so that, under ideal conditions, the wave loses no power while propagating. Due to total reflection at the walls, waves are confined to the interior of a waveguide.





Electric field in a hollow metal waveguide.

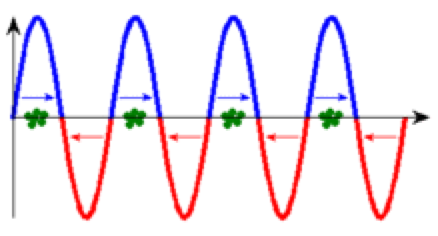
WAVEGUIDE: ACCELERATION OF ELECTRONS

Standing-Wave

Electrons "see" constant repelling electric field upstream and attracting electric field downstream.

Energy control:

RF Power per cavity

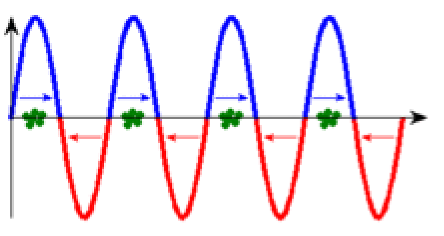


Travelling-Wave

Electrons are captured and accelerated by the differential electric field components of RF and are travelling with wave.

Energy control:

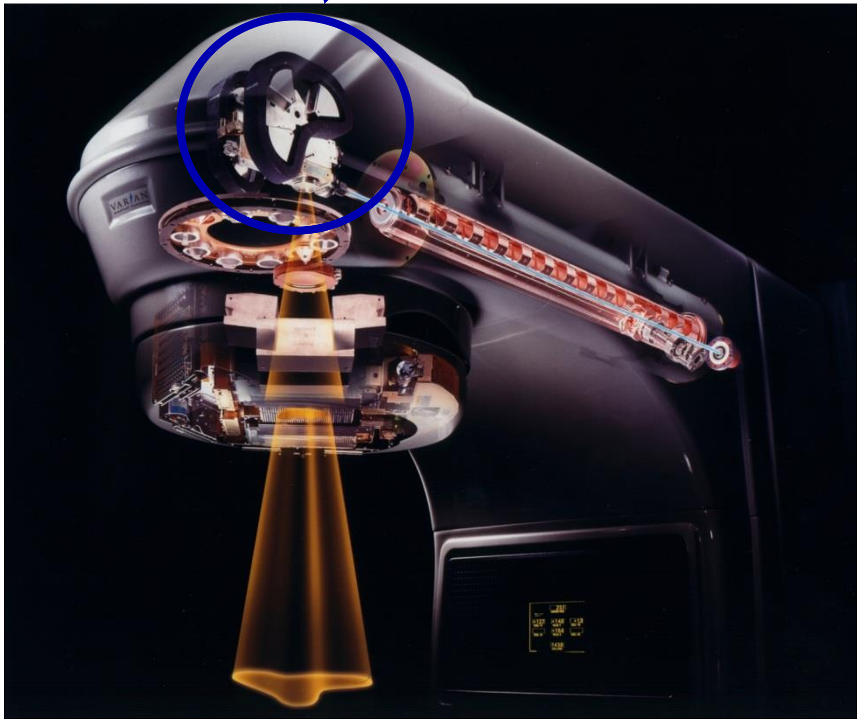
RF Frequency



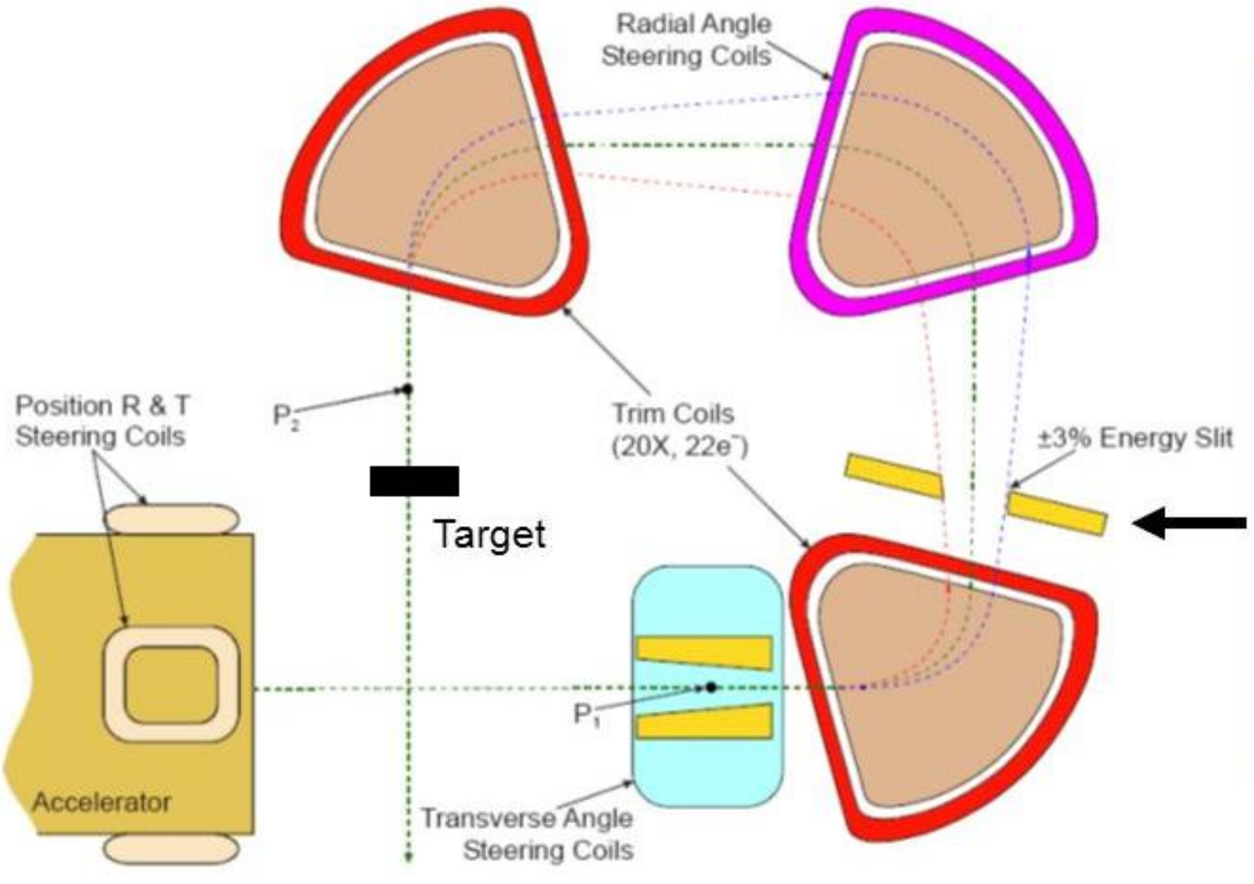
BENDING MAGNET

Two features:

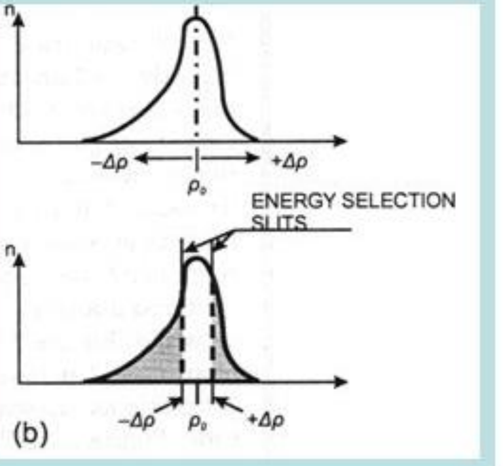
- Bends electrons in the direction of the patient
- Energy selection



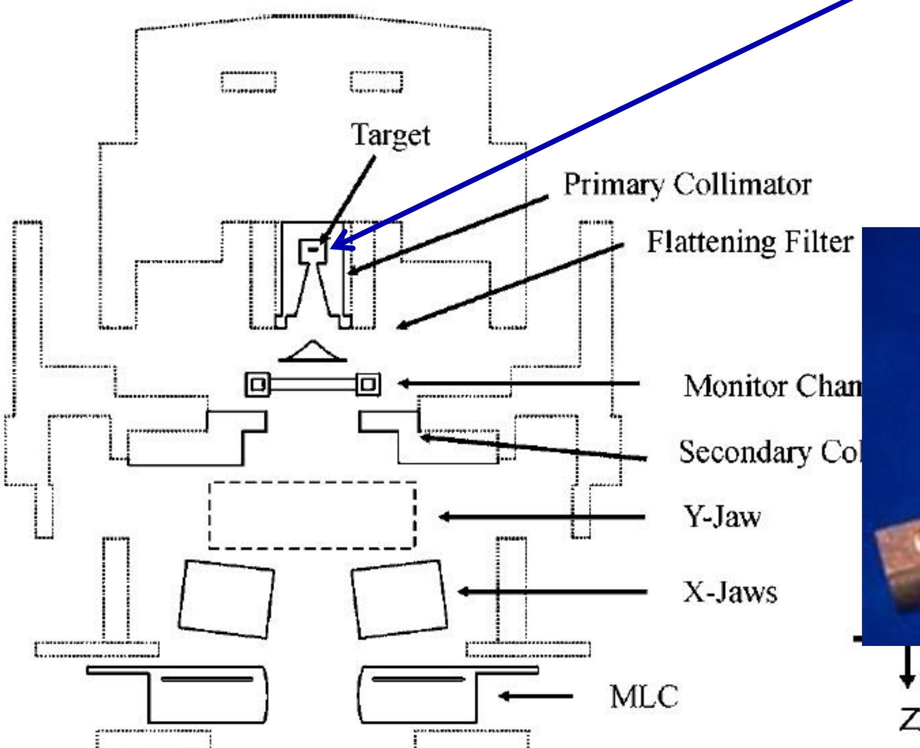
BENDING MAGNET



Energy slit:
Slit at position with non-zero dispersion



BREMSSTRAHLUNGS-TARGET

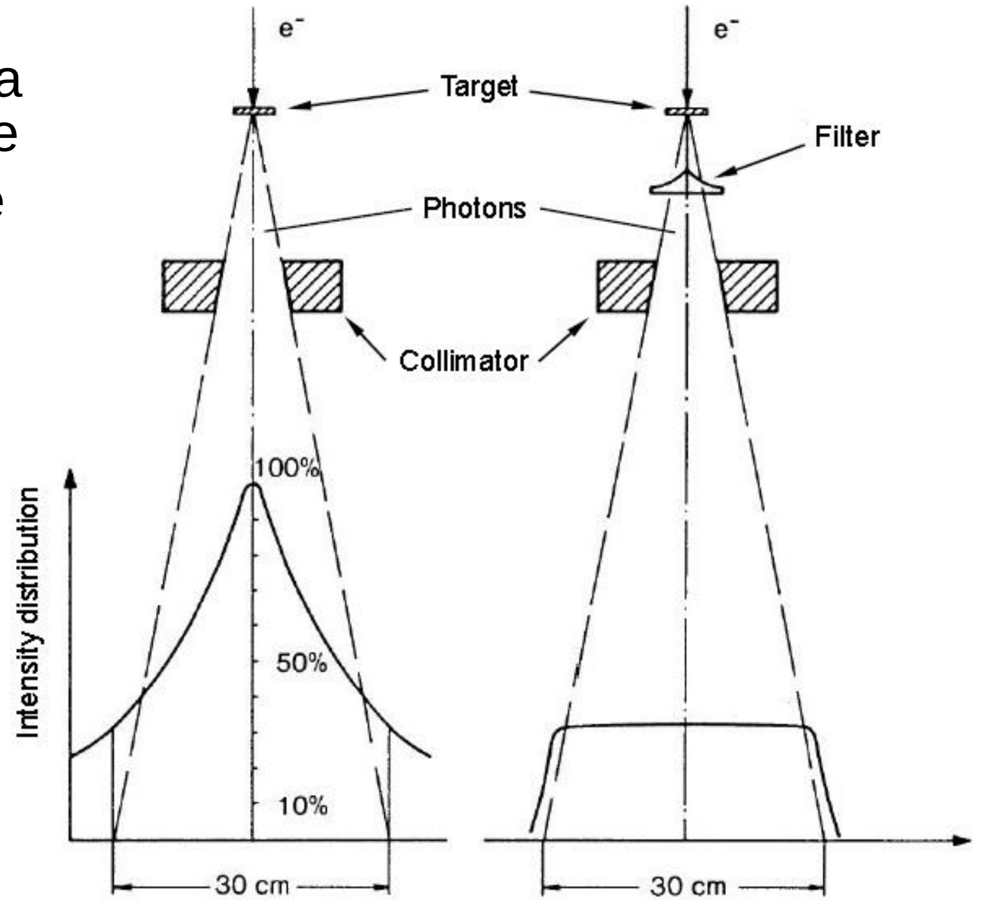


Target

Conversion of electron beam to Bremsstrahlung (target)

FLATTENING FILTER

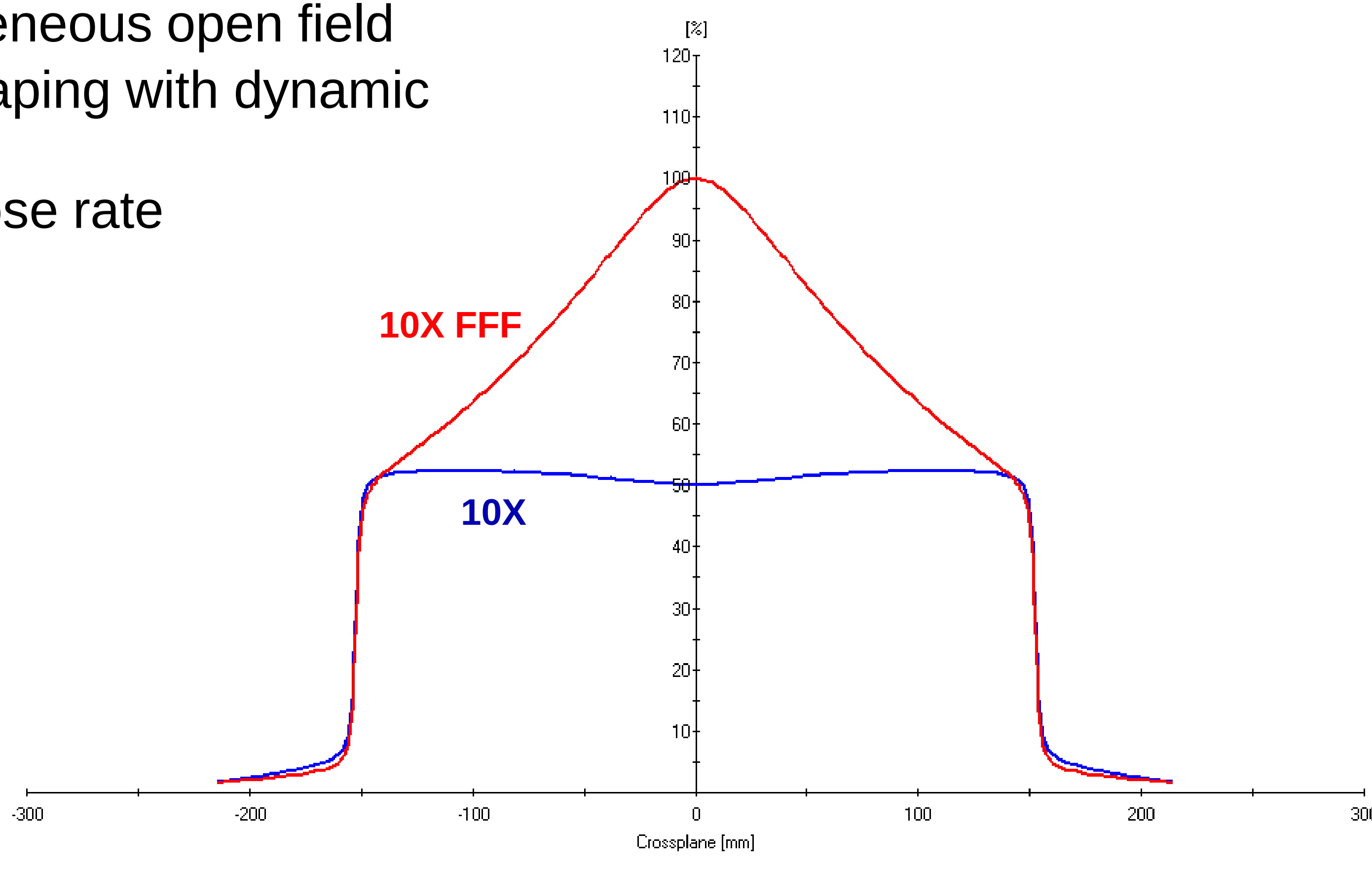
- Treatment with photons requires wide beams with a flat transverse beam profile
- Filter: used to homogenise transverse beam profile
- Reduction of total beam intensity
- Production of neutrons



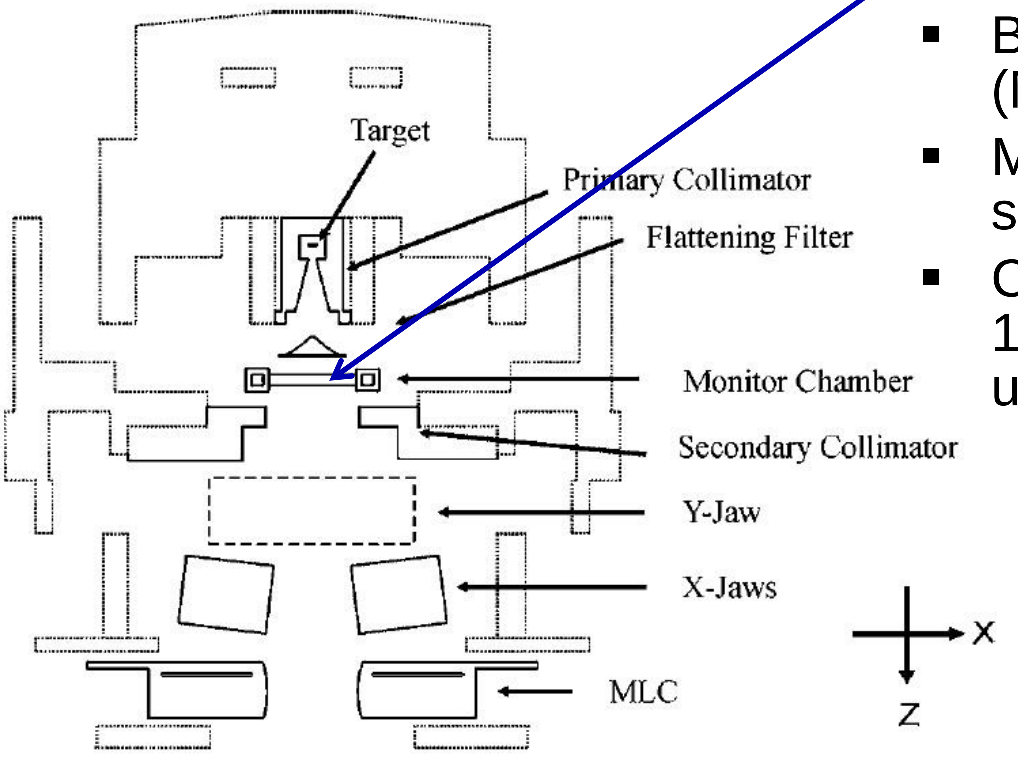
FLATTENING FILTER FREE RT

Omit flattening filter

- Inhomogeneous open field
- Beam shaping with dynamic MLC
- Higher dose rate



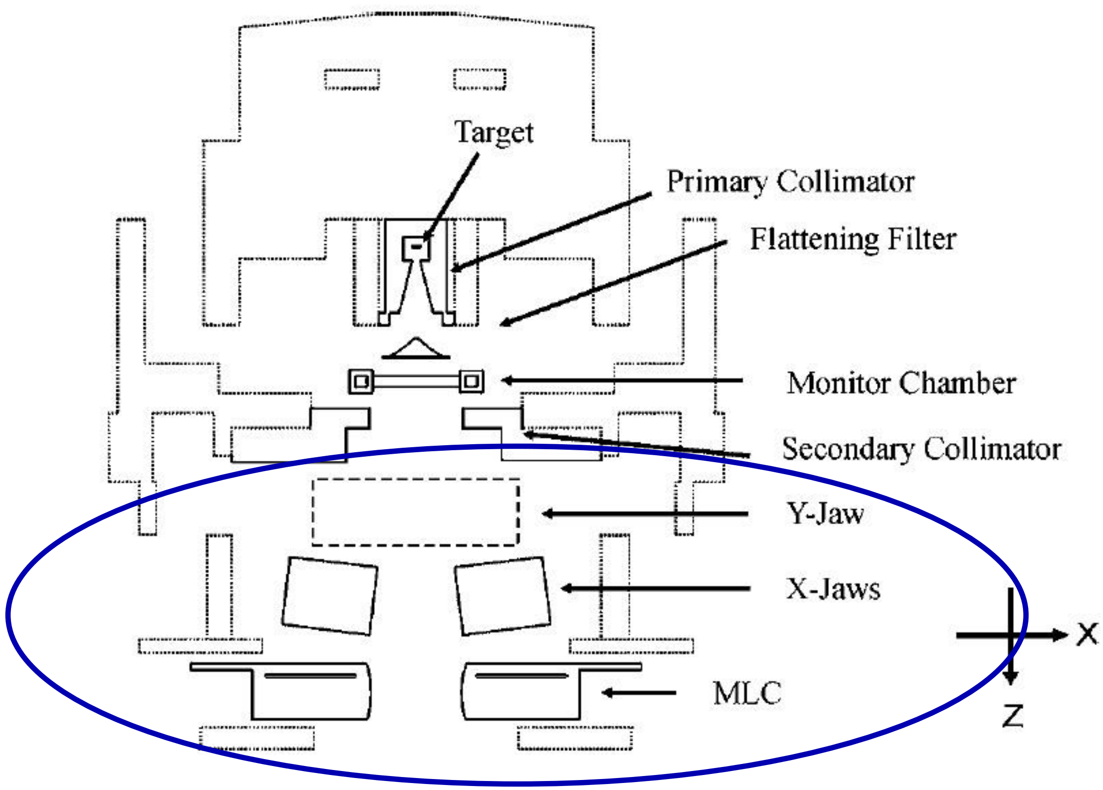
MONITOR CHAMBER



Measurement of photon fluence

- Beam output in monitor units (MU)
- Measurement of beam symmetry
- Calibrated so that
  1 MU = 1cGy
  under defined conditions

BEAM SHAPING AND INTENSITY MODULATION



INTRODUCTION: DESIGNING A TREATMENT BEAM

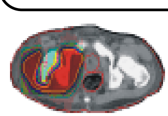
The radiation oncologist must know his/her radiations:

Interactions of individual particles with single atoms

- **photons and electrons**
- **Protons (later)**

Interactions of a photon beam in bulk matter

- **in a water bucket**
- **in simple inhomogeneities**



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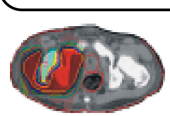
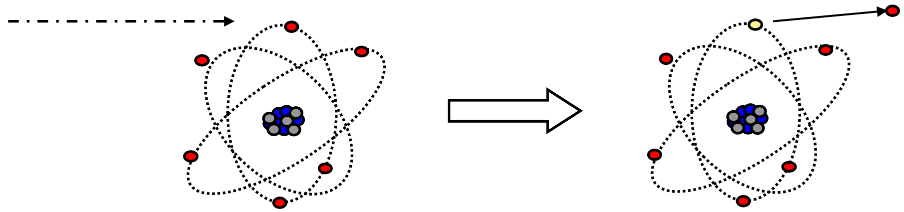
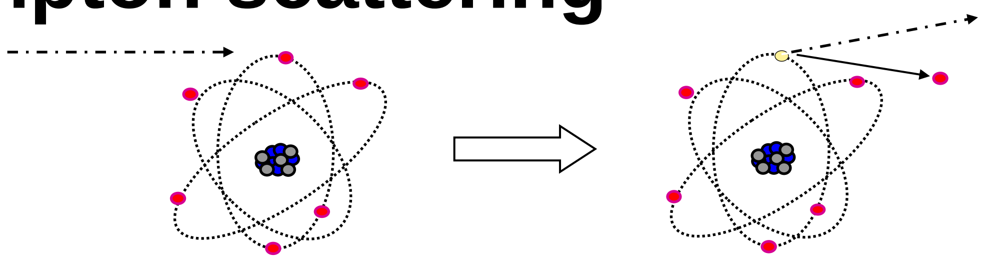


INTERACTION OF PHOTONS WITH INDIVIDUAL ATOMS

Photoelectric effect

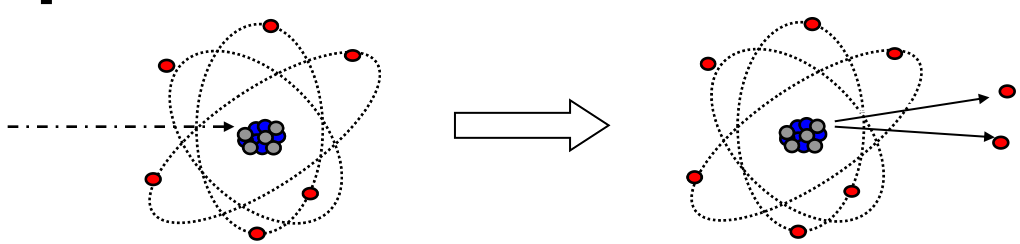


Compton scattering



dominates in the energy range of interest

Pair production



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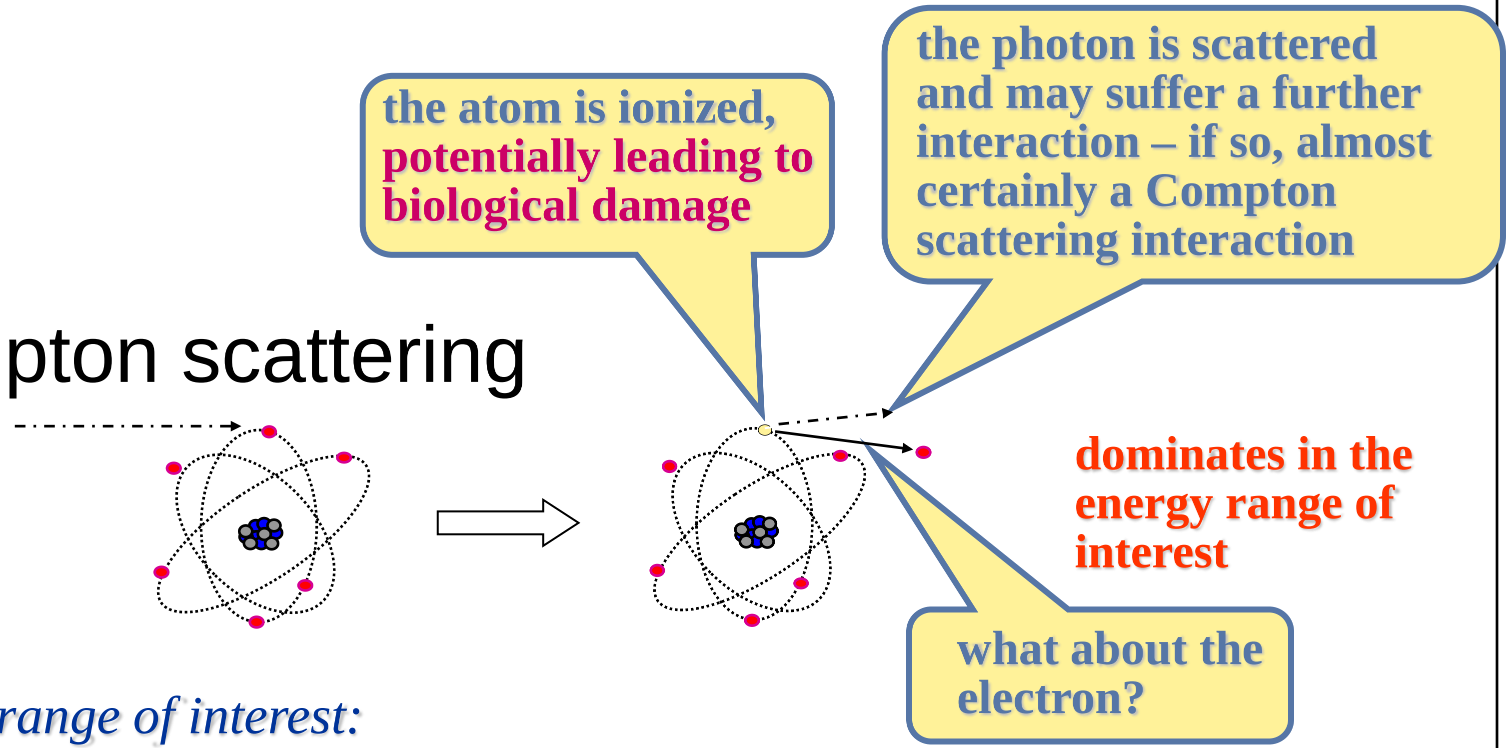
INTERACTION OF PHOTONS WITH INDIVIDUAL ATOMS

Compton scattering



dominates in the energy range of interest

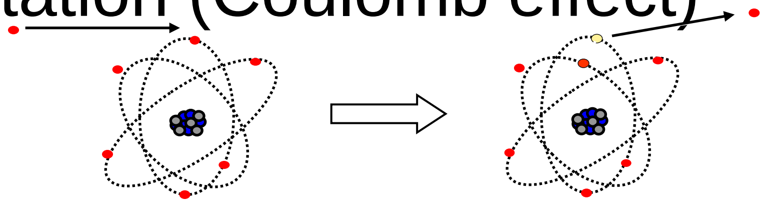
In the energy range of interest:

both the scattered photon and the ejected electron tend to go off in the near-forward direction (within ~10°)

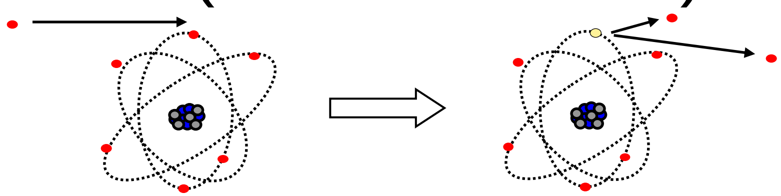
the scattered photon and the ejected electron partition the incident photon’s energy near-arbitrarily

ELECTRON INTERACTIONS

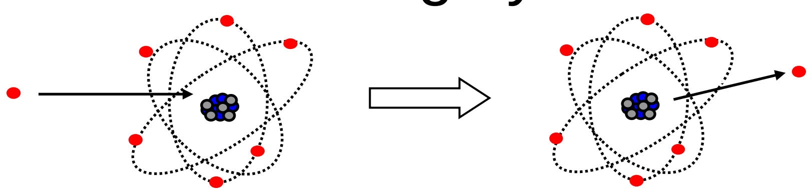
Excitation (Coulomb effect)



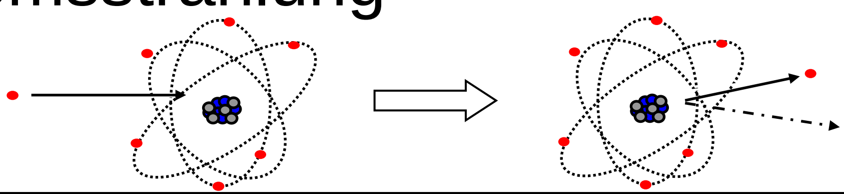
Ionization (Coulomb effect)



Coulomb scattering by the atomic nucleus



Bremsstrahlung



dominate (in the energy range of interest)

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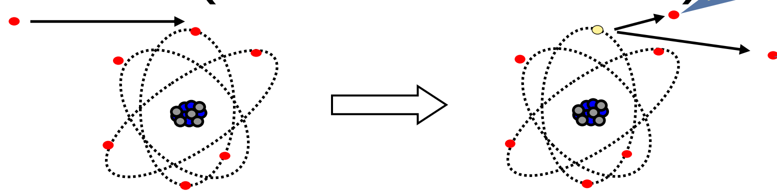
ELECTRON INTERACTIONS

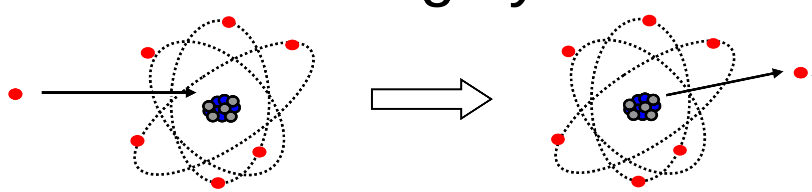
an atomic electron is knocked out of the atom, thereby ionizing it – **potentially leading to biological damage**

Ionization (Coulomb effect)



meanwhile, the incident electron will go off and almost certainly induce further ionizations

Coulomb scattering by the atomic nucleus



the incident electron may be scattered by the positively charged nucleus – the main effect of which is to alter its direction

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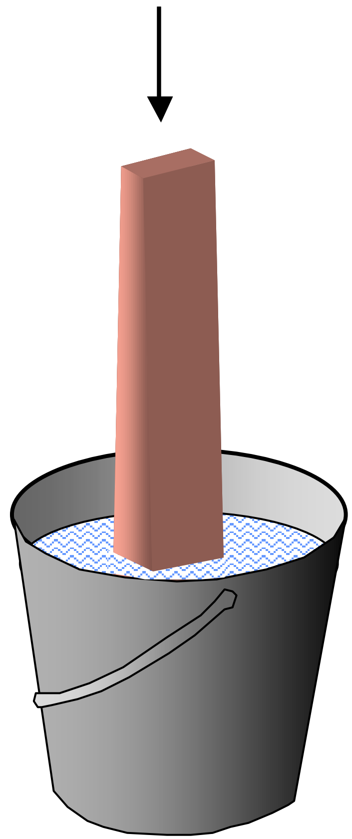
RELATIVE LIKELIHOODS OF INTERACTIONS
(in the energy ranges of interest)

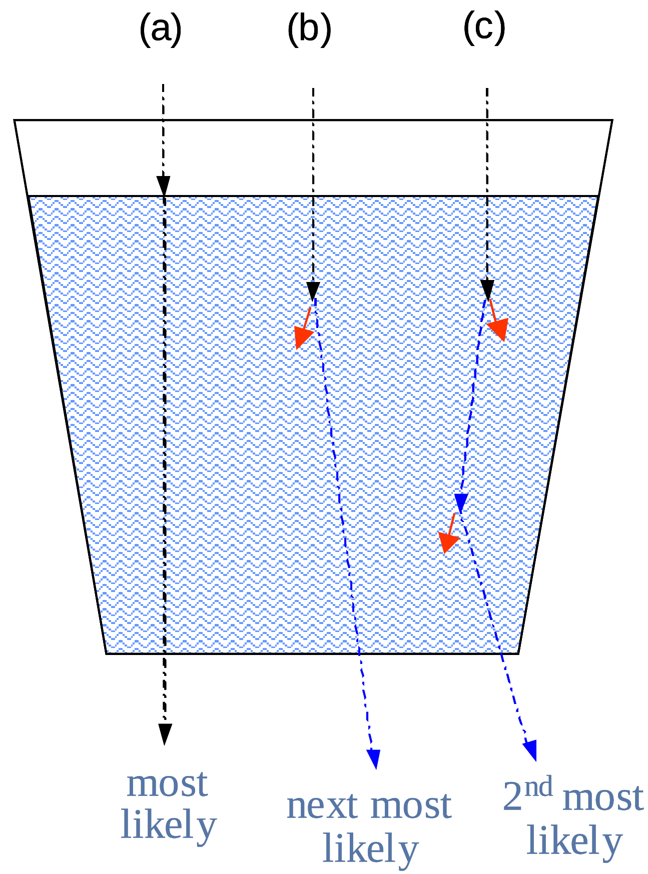
- Photons
  - Being neutral, photons interact with atoms only weakly – via the interactions of their electrical/magnetic fields with atomic constituents
    - the mean free path of a photon in the energy range of interest is very approximately 20 cm (i.e. a few percent chance of a single interaction per centimeter of travel)
- Electrons
  - Being charged, electrons interact with the charged constituents of atoms (orbiting electrons and the nucleus) very readily
    - a few-MeV electron will, together with secondary electrons that it sets loose, ionize some tens to hundreds of thousands of atoms per centimeter of travel

DOSE DISTRIBUTION IN A WATER BUCKET



PHOTONS in bulk matter

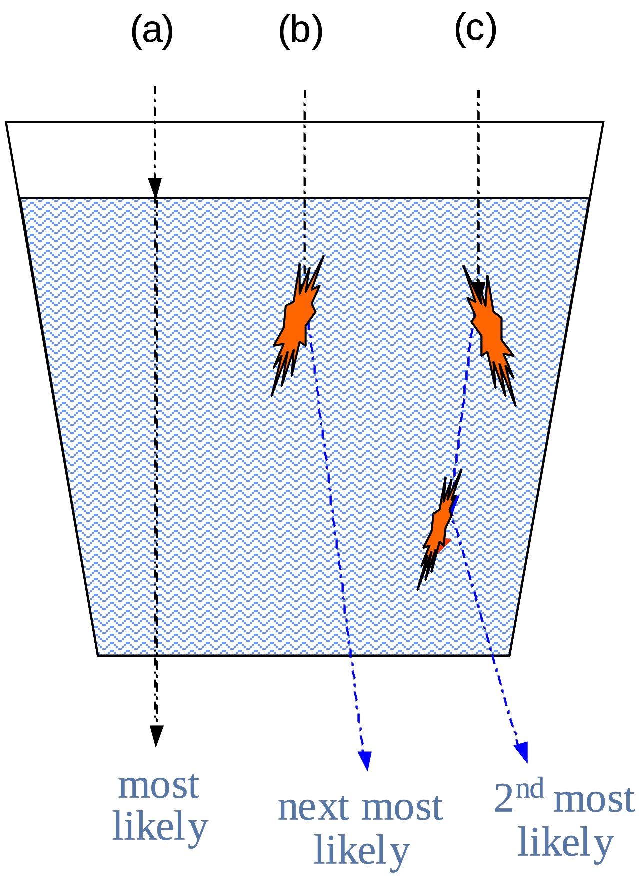
Q: What is the most likely thing to happen?



A: Absolutely nothing!

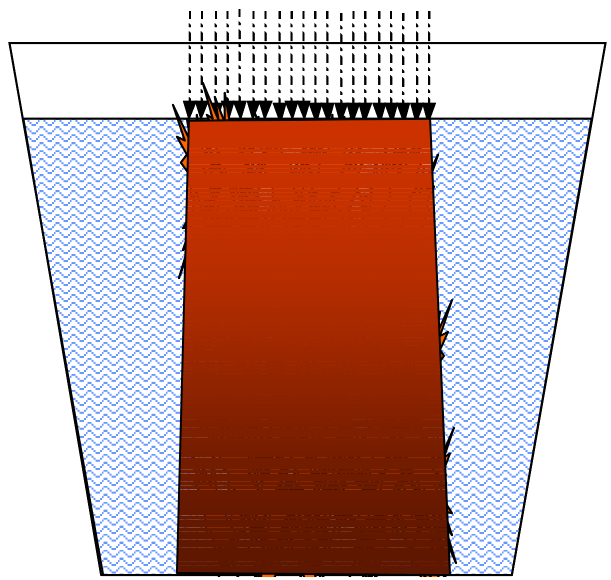
PHOTONS in bulk matter

Q: What is the most likely thing to happen?



A: Absolutely nothing!

PHOTONS in bulk matter



DOSE

- The interactions of radiations with atoms result in the transfer of energy from the particles to the medium
- The energy loss per unit mass is called the dose

  1 Joule / kilogram = 1 Gray (Gy)
- The energy loss has two consequences:

  it can heat up the medium (via vibration and rotation of molecules)

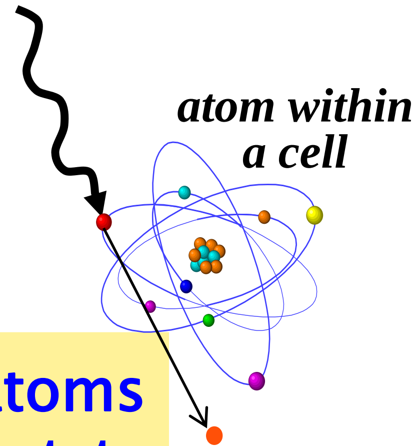
  it can damage the molecules of the medium

> 96% of energy appears as heat

Dose is merely a surrogate for what we care about – namely, biological effects

HOW DOES BIOLOGICAL DAMAGE OCCUR?
A cascade of effects

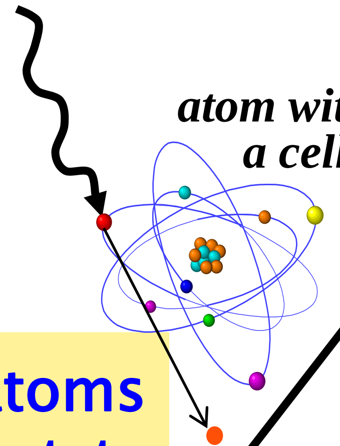
physics



1) ionize atoms
2) vibrate/rotate
→ heat

HOW DOES BIOLOGICAL DAMAGE OCCUR?
A cascade of effects

physics



chemistry

1) ionize atoms
2) vibrate/rotate
→ heat

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

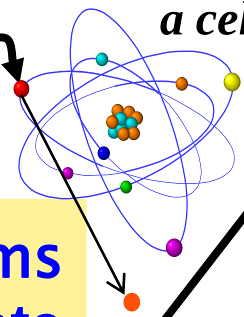
$H_2O^+ + e^- \rightarrow H^\bullet + OH^\bullet$

i.e. formation of highly reactive free radicals

HOW DOES BIOLOGICAL DAMAGE OCCUR?
A cascade of effects

physics

atom within a cell



1) ionize atoms
2) vibrate/rotate
→ heat

chemistry

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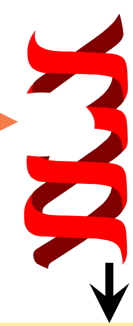
i.e. formation of highly reactive free radicals

biology

DNA

free radical +
(or direct ionization which breaks a molecular bond)



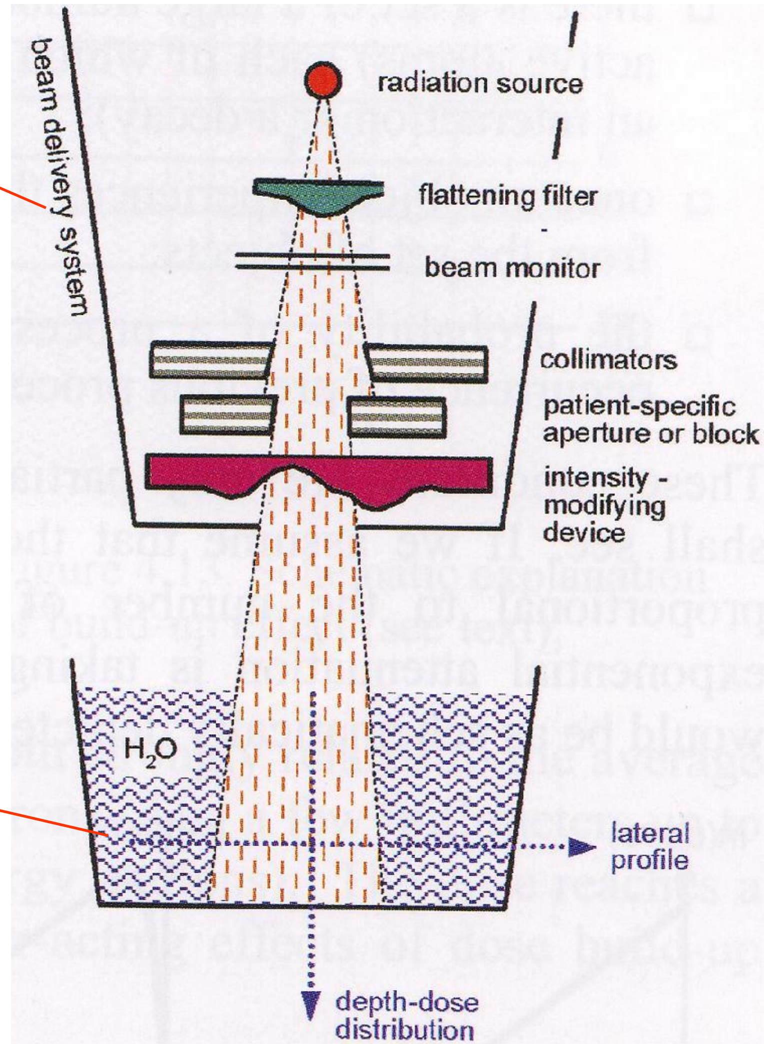
e.g. single- or double-strand DNA break → lethally damaged cell

tumor / whole organ response

DESIGN OF A UNIFORM RECTANGULAR TREATMENT BEAM

- **Beam delivery system – usually mounted on the gantry**

- **Dose distribution in the water phantom?**



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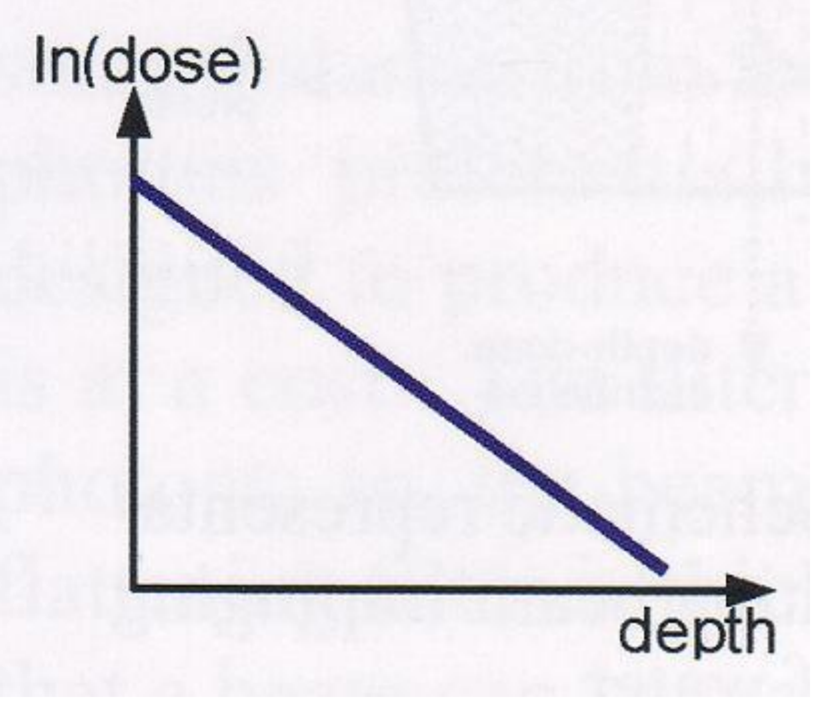
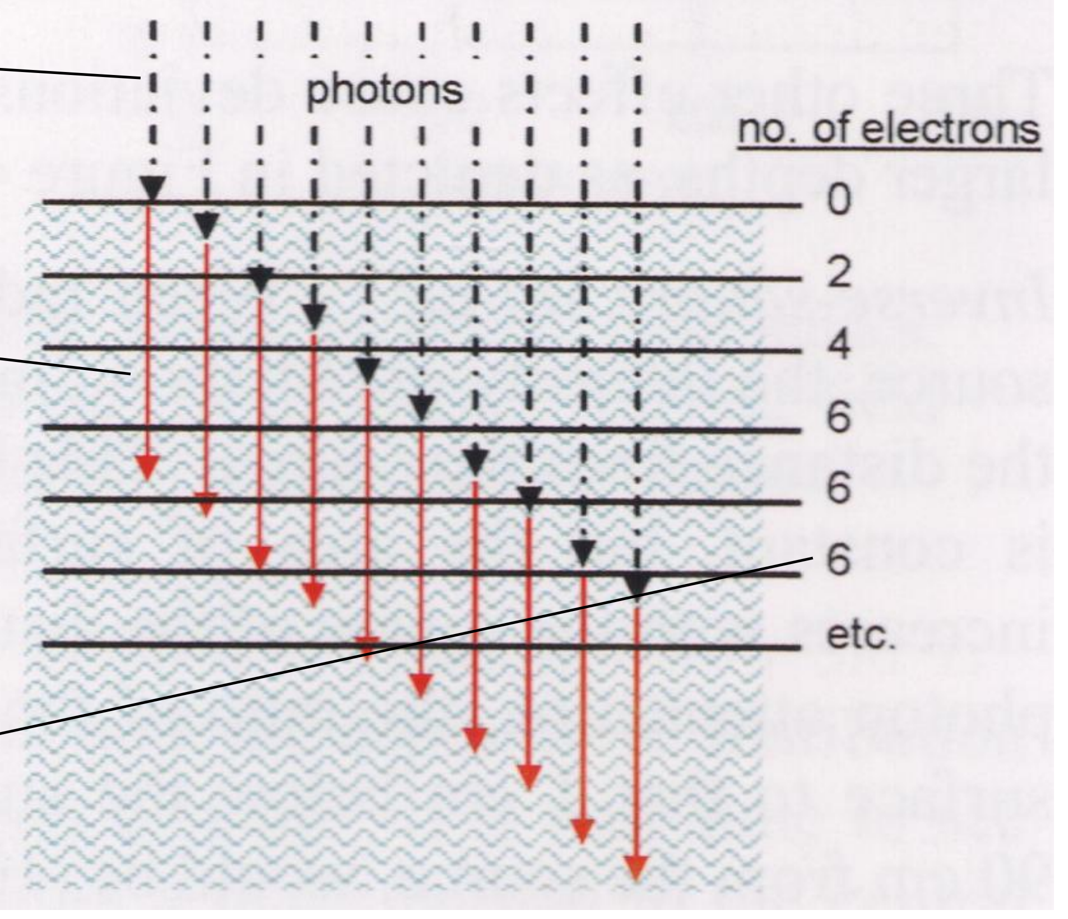
DISTRIBUTION OF THE DOSE IN DEPTH

- **Photons are lost upstream (Compton)**
- **Dose decreases proportional to photon number?**
- **Attenuation is exponential in depth:**
  $n = n_0 \exp(-\mu d)$



DISTRIBUTION OF THE DOSE IN DEPTH

- **Photons impinge on a block of material; they have their first interaction at different depth**
- **Photons loose electrons which move forward for a fixed distance**
- **The number of electrons increases with depth until reaching an "equilibrium"**



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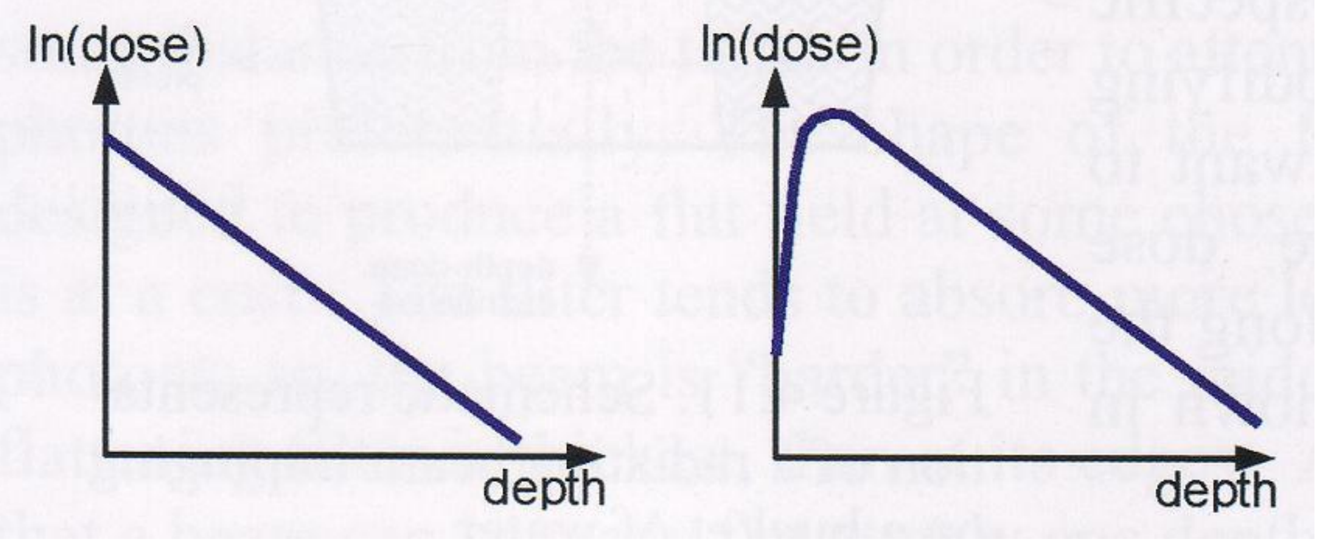
- ***Dose build-up***
- ***Skin-sparing-effect***



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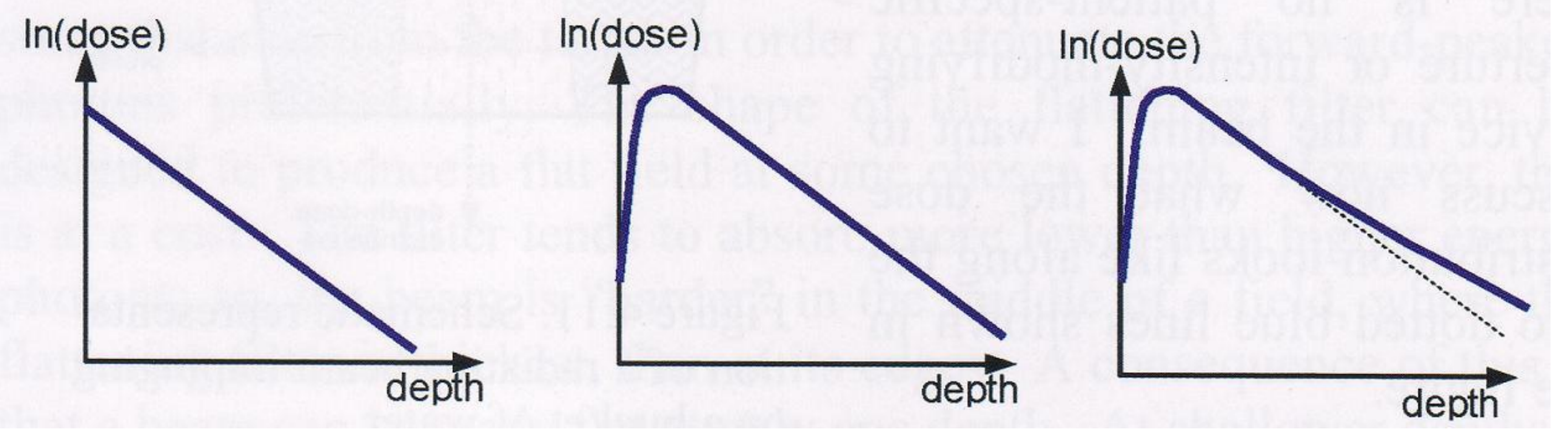
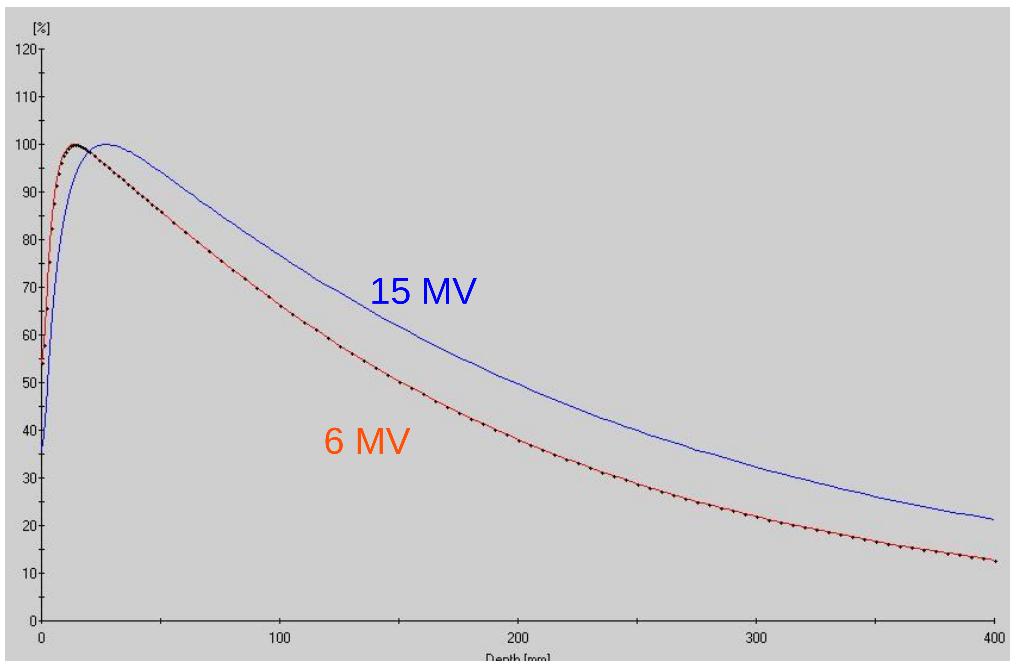
- **Dose is proportional to the energy deposited by secondary electrons**
- ***Dose build-up***
- ***Skin-sparing-effect***
- **Photon beam has a spectrum of energies**
- **Compton effect energy dependent**
- **At larger depth more high energy photons (beam hardening)**



DISTRIBUTION OF THE DOSE IN DEPTH

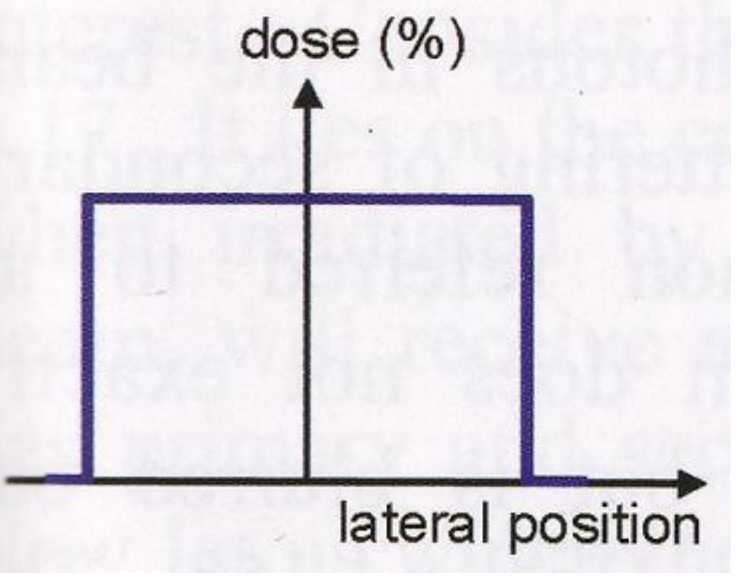
Other effects causing deviation of exponential fall-off:

- ***Inverse-square-law:*** **Intensity diminishes with the inverse square of the distance from the source**
- ***Scattered photons:*** **Compton interactions produce sea of softer photons which would lead to more-than- exponential fall-off (beam-size-dependent)**



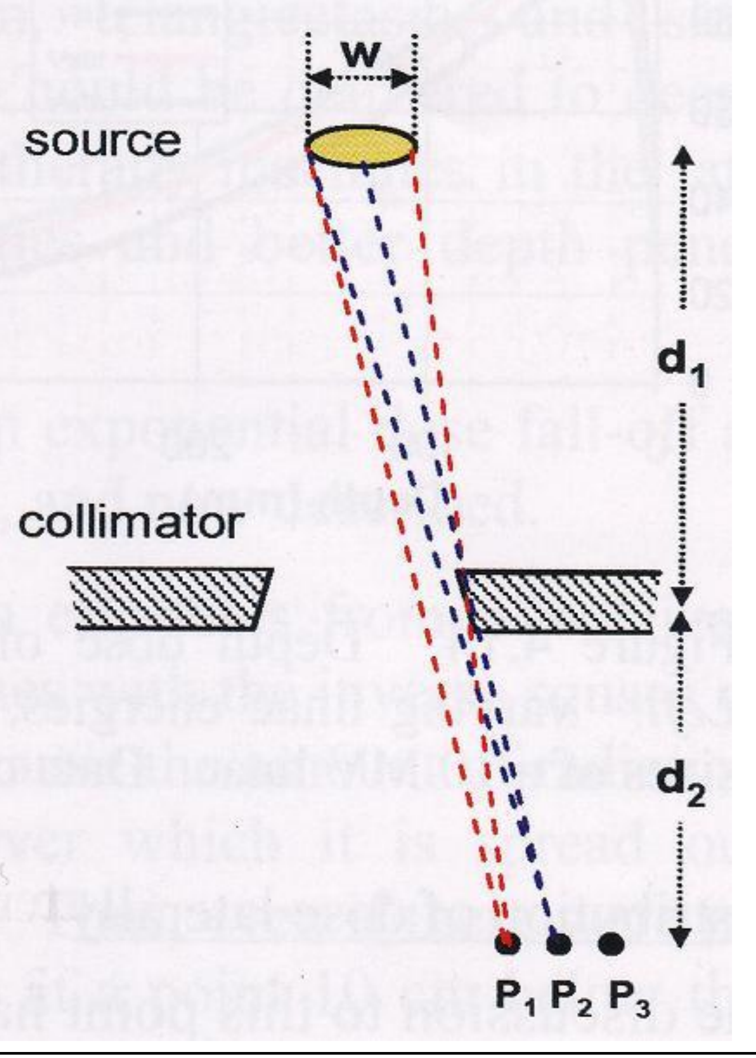
DISTRIBUTION OF DOSE LATERALLY

- *Ideal beam:* **with point source, perfect collimation and energy deposition at the side of interaction**
- **Step-function-like dose distribution**



DISTRIBUTION OF DOSE LATERALLY

- **Radiation source is of finite size**
- **Point *P_2* "sees" only half of the beam**
- **Purely geometrical effect**
- **Penumbra is smaller as closer the collimator is to the patient (width ~ *d_2/d_2*)**



DISTRIBUTION OF DOSE LATERALLY

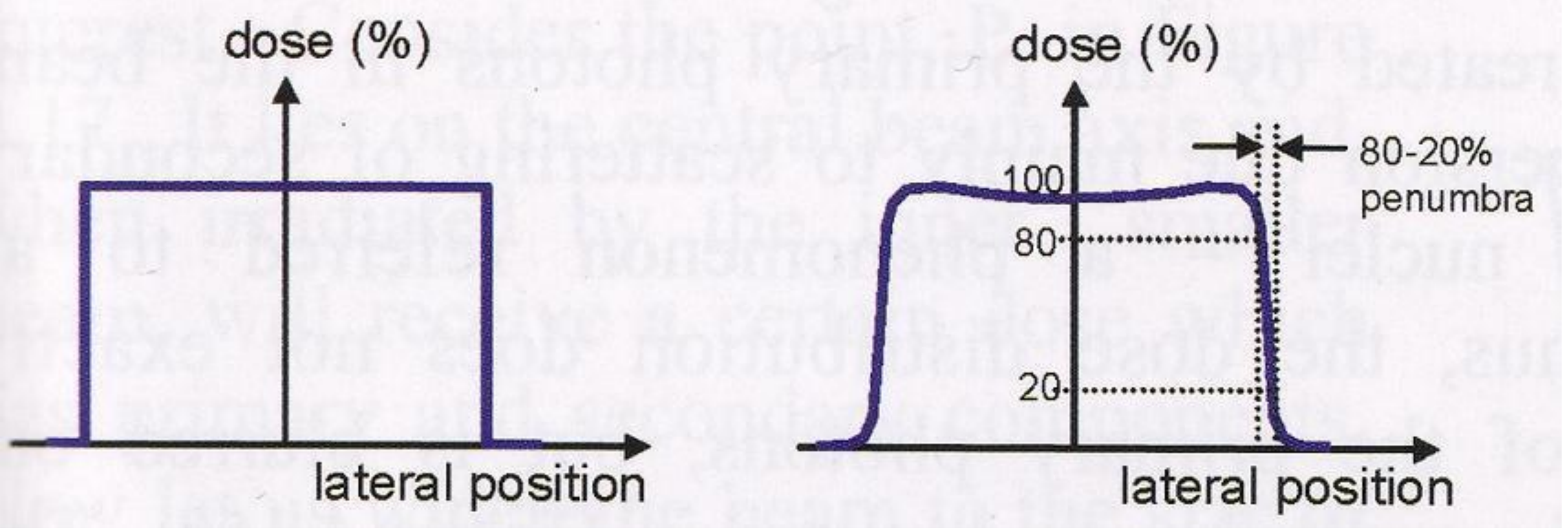
- ***Ideal beam***

Creation of penumbra:

- **Finite size of the radiation source**
- **Secondary electrons move laterally**

Cupping:

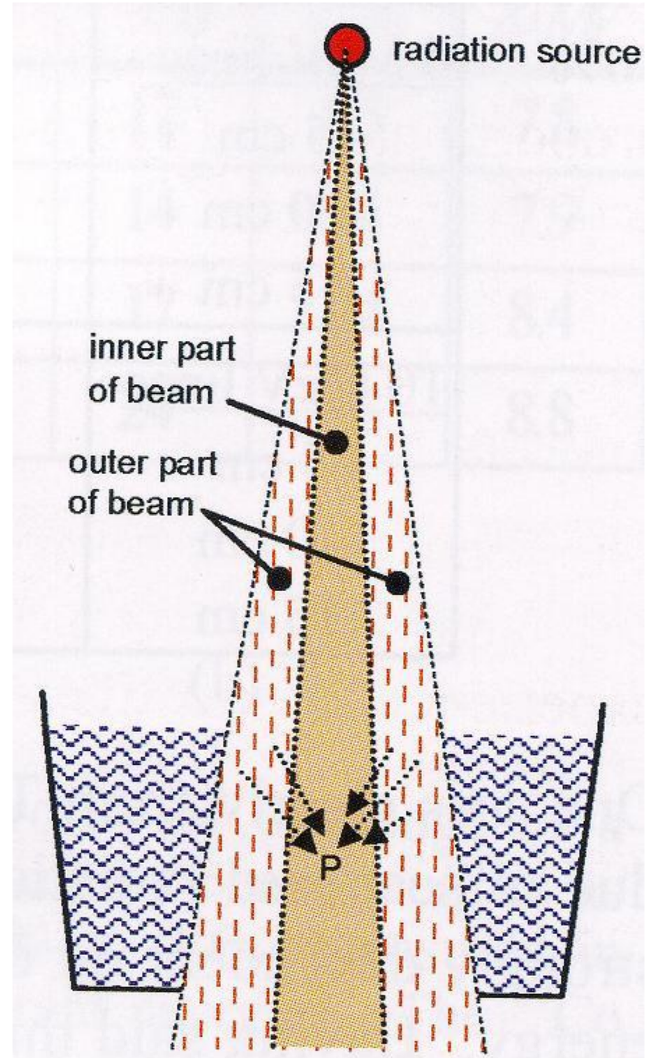
- **Beam hardening (flattening filter)**



DISTRIBUTION OF DOSE LATERALLY

Dose due to scattered radiation

- ***Energy:*** **Compton scatter higher for lower energy**
- ***Depth:*** **increasingly fraction of scattered photons with depth**
- ***Field size:*** **Point P receives independent of field size the same primary radiation, however, scattered radiation increases with field size**



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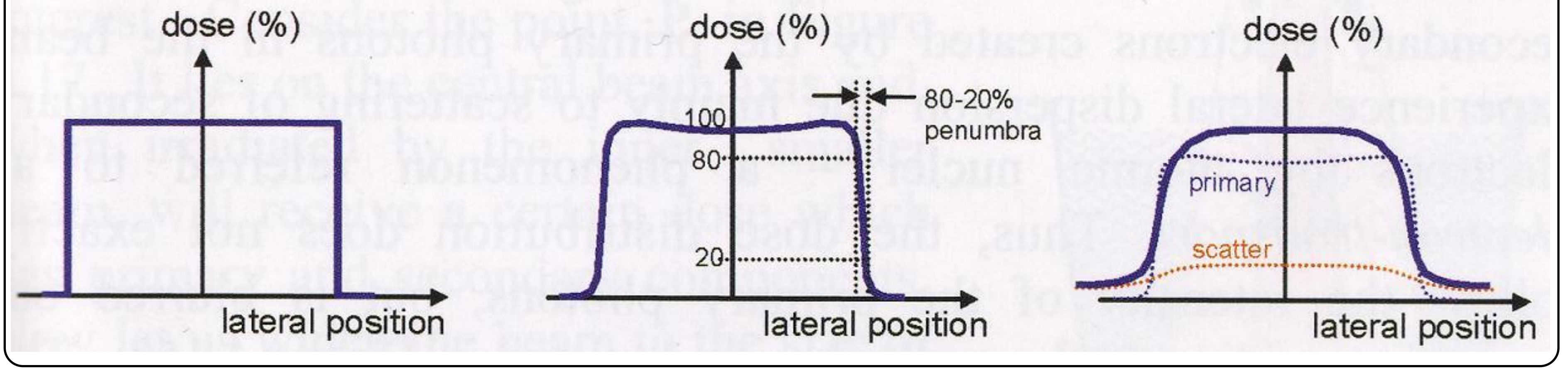
DISTRIBUTION OF DOSE LATERALLY

- ***Ideal beam***

- ***Creation of penumbra***
- ***Cupping***

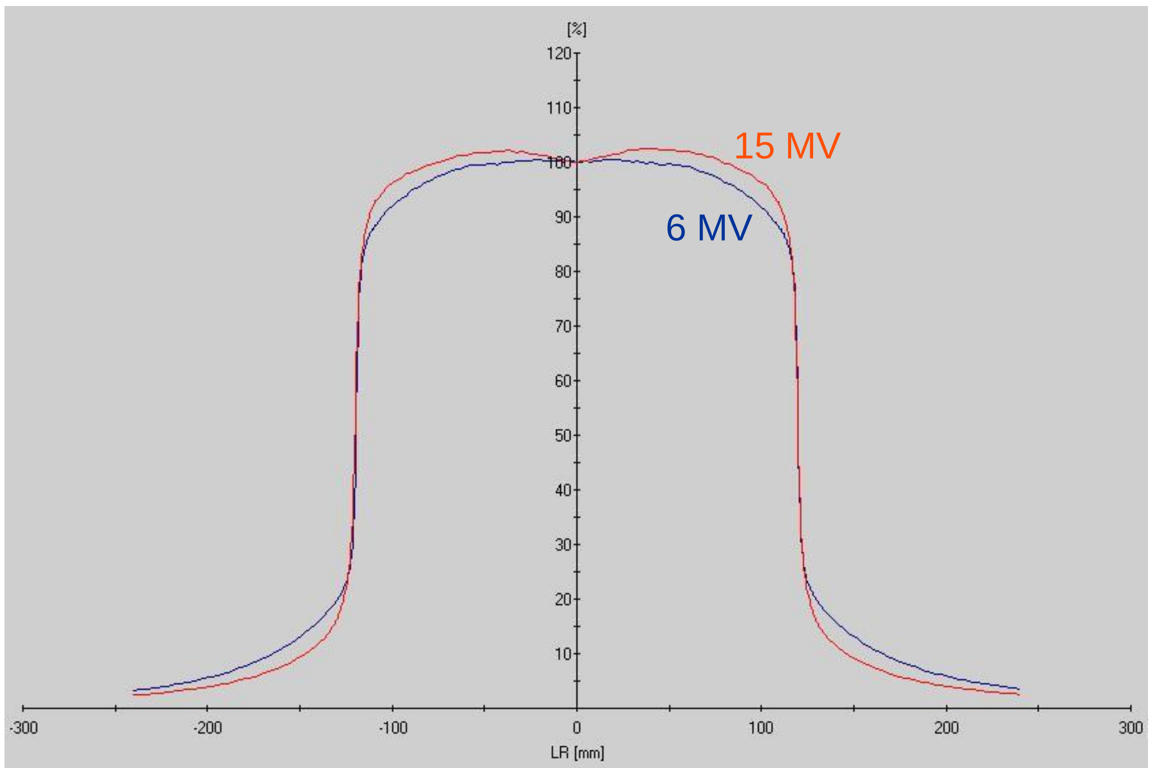
Effect of scattered radiation:

- **Lateral distribution of scattered radiation is broad**
- **Blurring the penumbra**

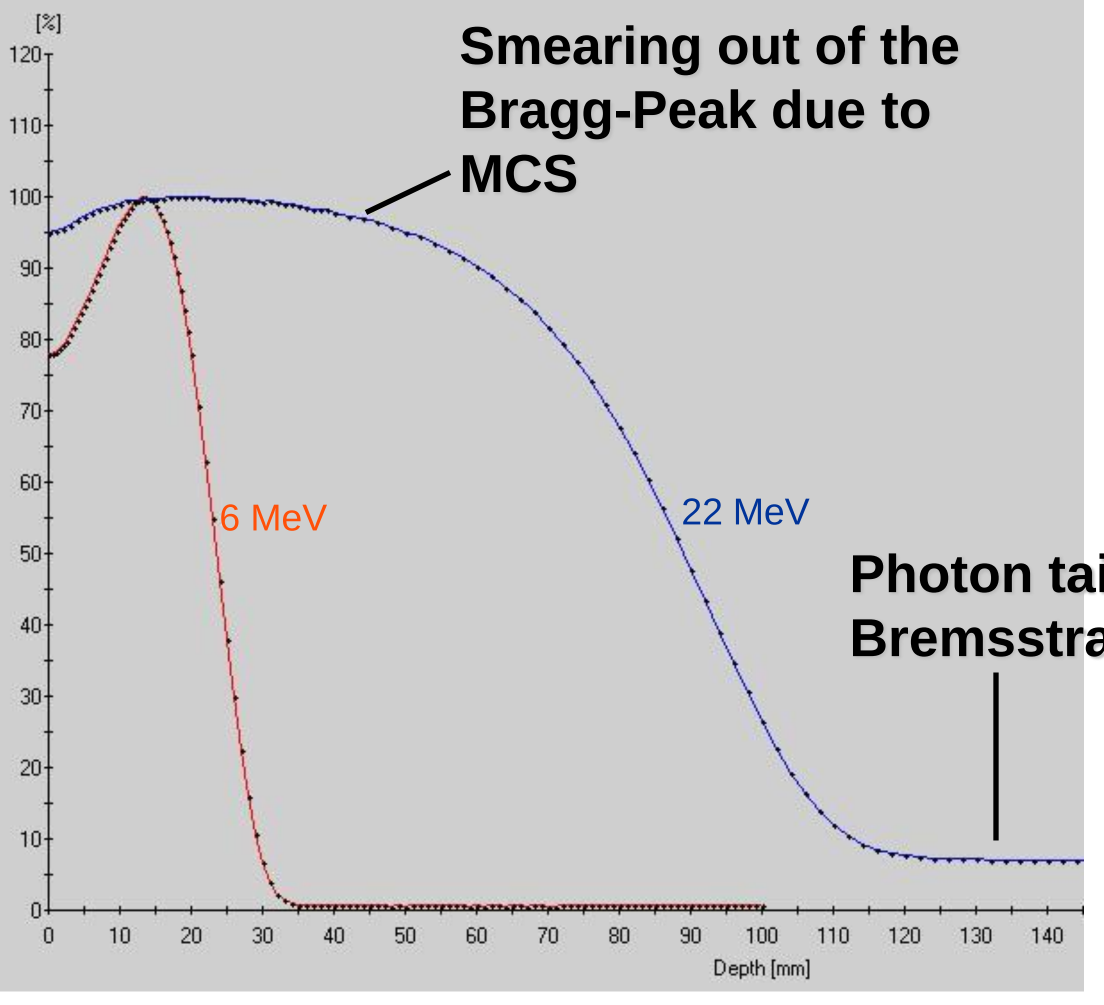


SUMMARY: Design of a treatment beam

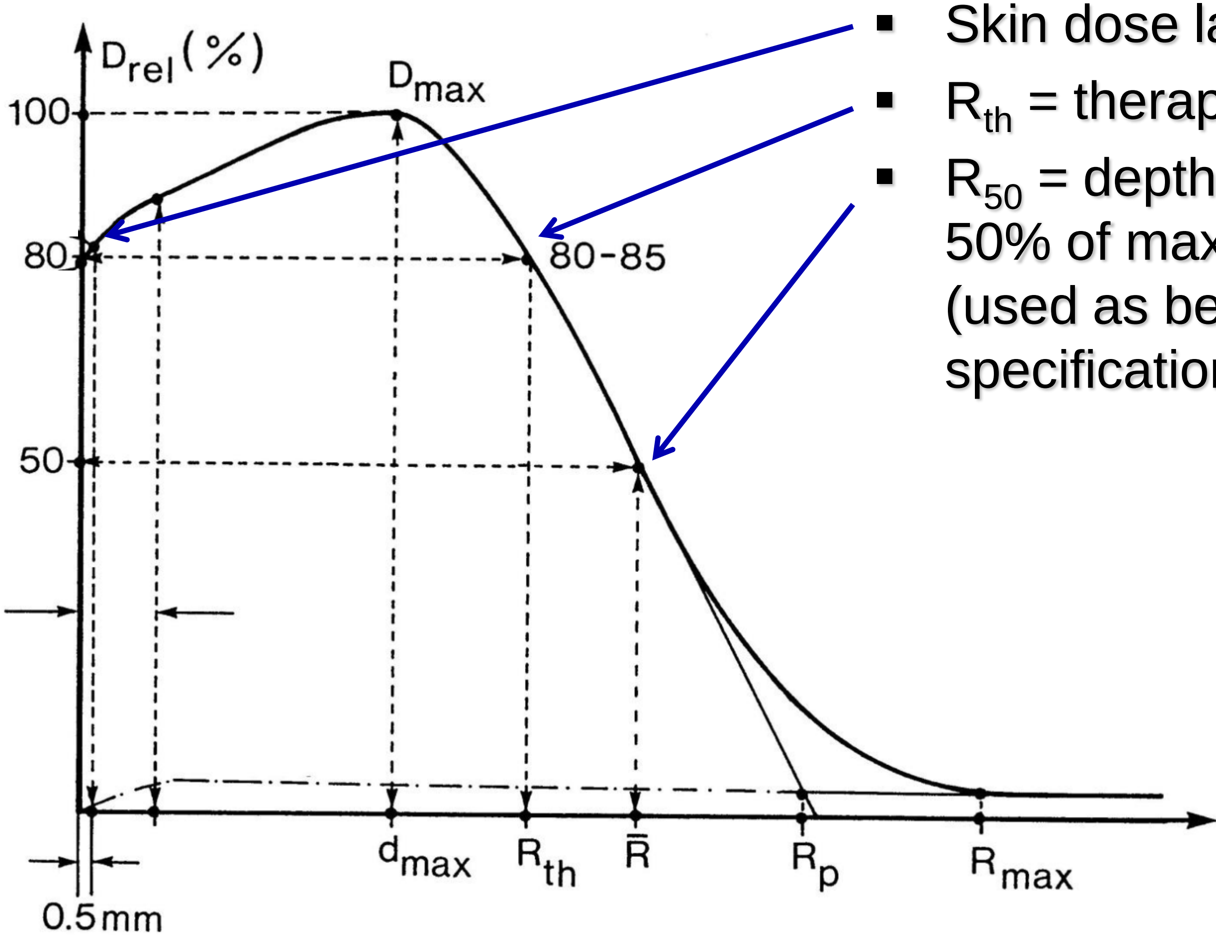
- **Interaction of individual photons and electrons**
- **Photons in a bulk of matter**
- **Generation and properties of a practical simple therapeutic photon beam**



ELECTRON DOSE DISTRIBUTIONS



CHARACTERISATION OF ELECTRON DOSE DISTRIBUTIONS

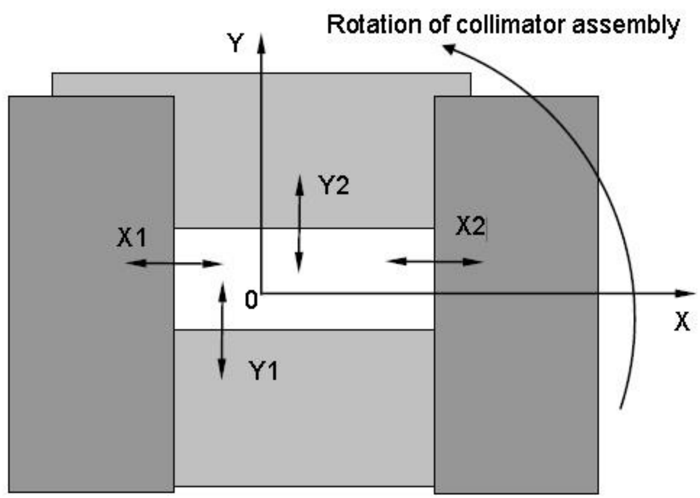


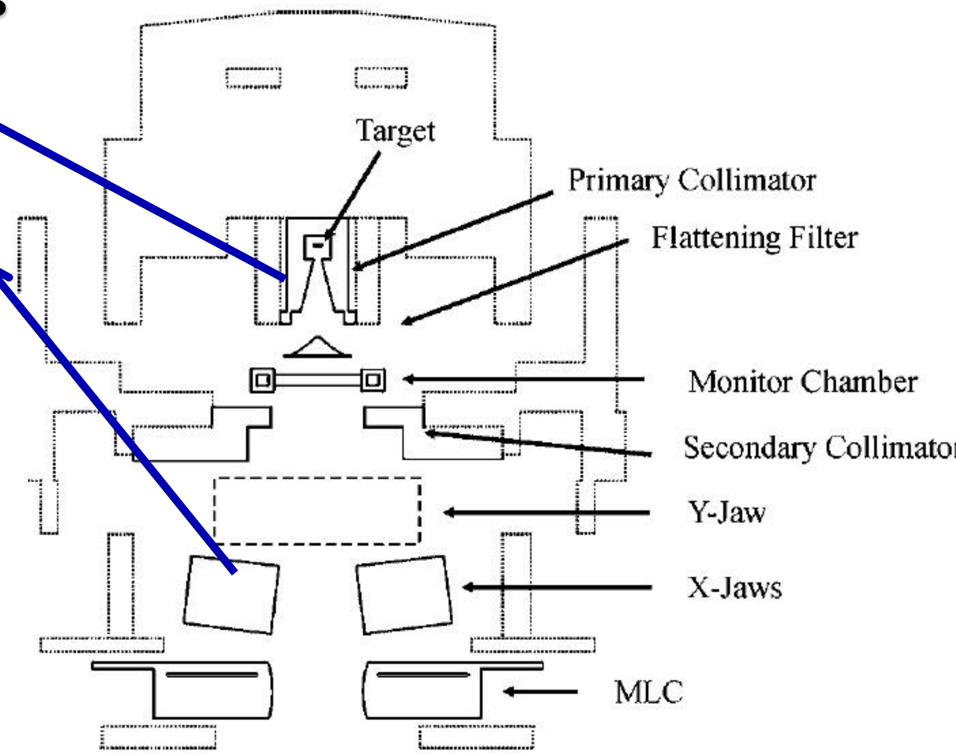
- Skin dose large
- R_{th} = therapeutic range
- R_{50} = depth where dose is 50% of maximum dose (used as beam quality specification for electrons)

SCULPTING A TREATMENT BEAM: STANDARD COLLIMATION

Collimation

- Primary collimators defines maximum field size
- Secondary collimators define actual field size in two transverse directions

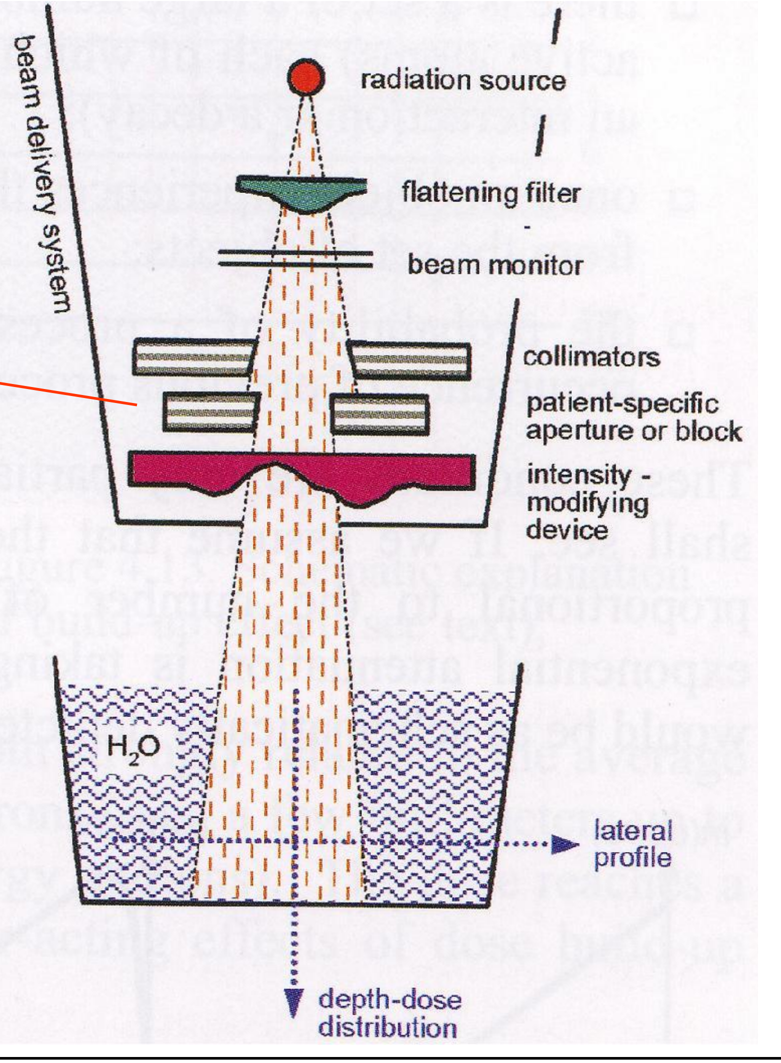




Illustrations from M. Goitein "Radiation Oncology: A Physicist's-Eye View" © Springer, 2007

SCULPTING A TREATMENT BEAM: PATIENT SPECIFIC BEAM SHAPING

- **Patient specific aperture in addition to rectangular collimation**

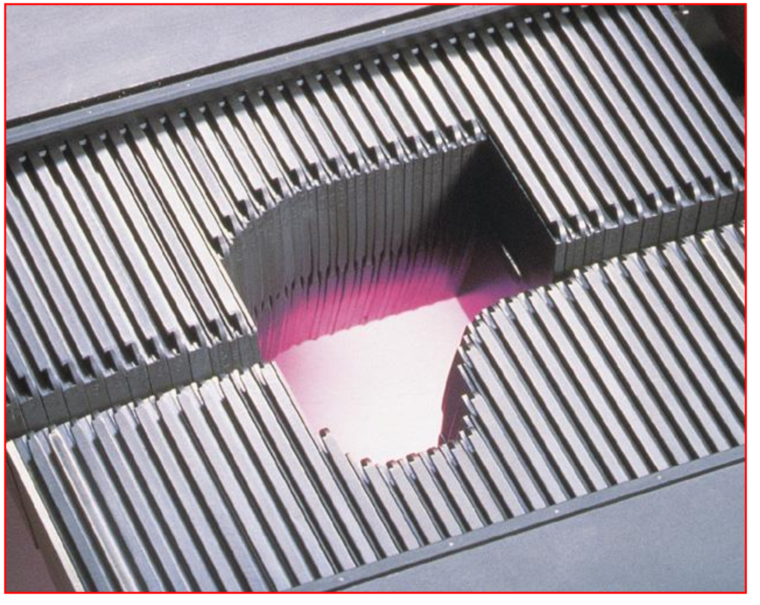


Illustrations from M. Goitein "Radiation Oncology: A Physicist's-Eye View" © Springer, 2007

SCULPTING A TREATMENT BEAM: BEAM SHAPING using MLC

Patient specific irregular blocking using multi-leaf collimator:

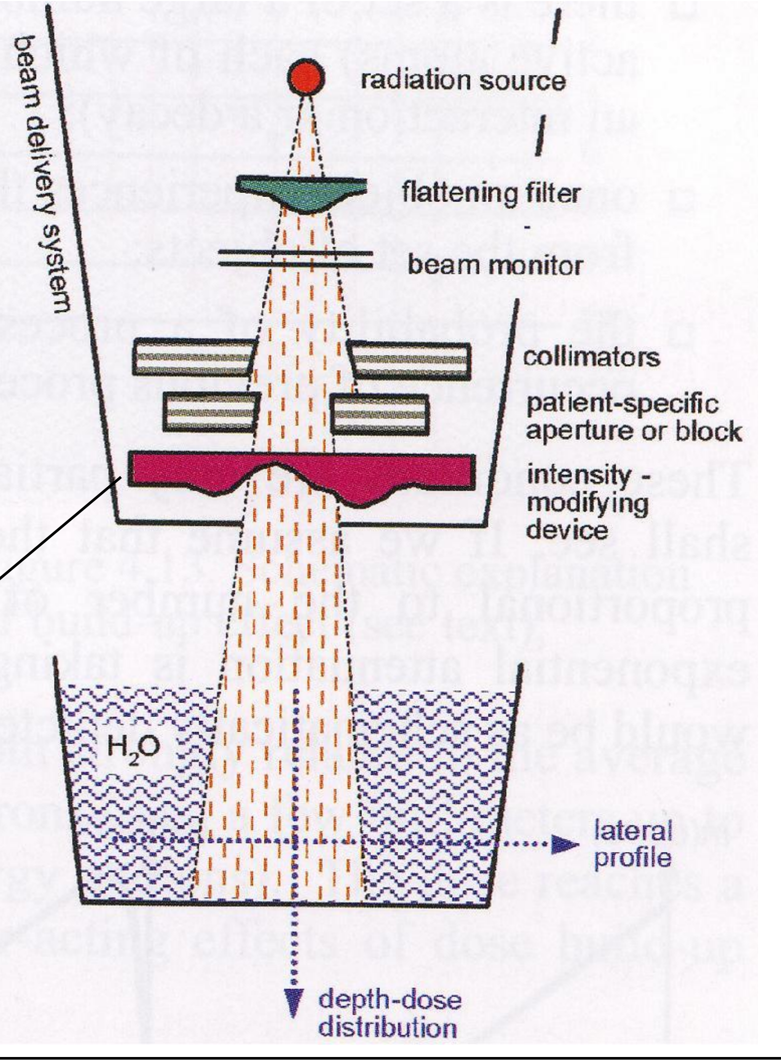
- Set of some hundred pair-wise opposing metal leaves
- Can be individually moved in and out by motors
- Each leaf has width of a few millimetres (at isocenter)
- No patient specific fabrication necessary
- Modification of beam shapes without entering the treatment room



SCULPTING A TREATMENT BEAM: STANDARDIZED INTENSITY MODULATION

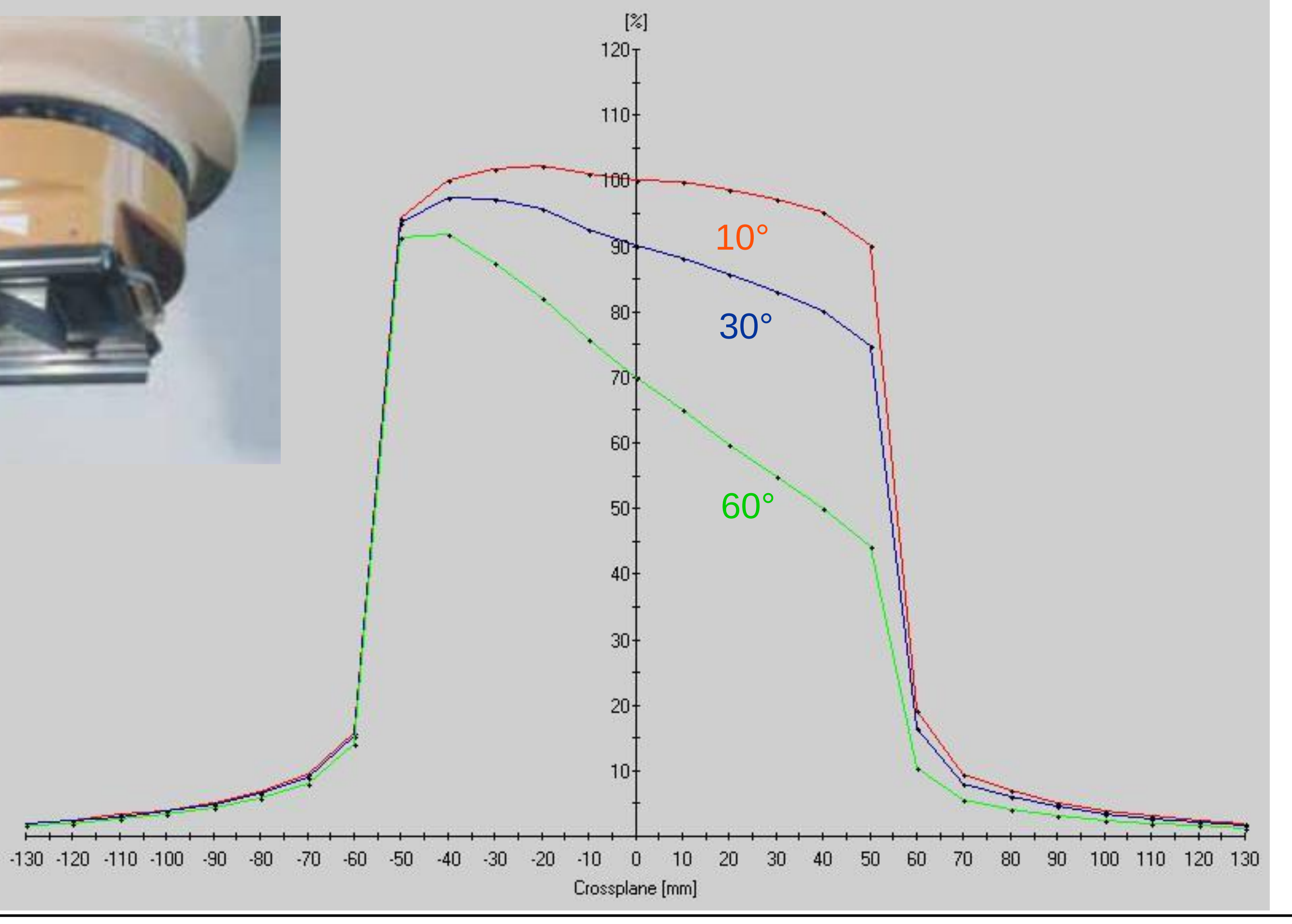
- So far only we looked at "open fields"
- Photon intensity is uniform throughout the field

- varying intensity distribution
- Interposing angle wedge-shaped hunks of metal
- Dynamic movement of the jaws



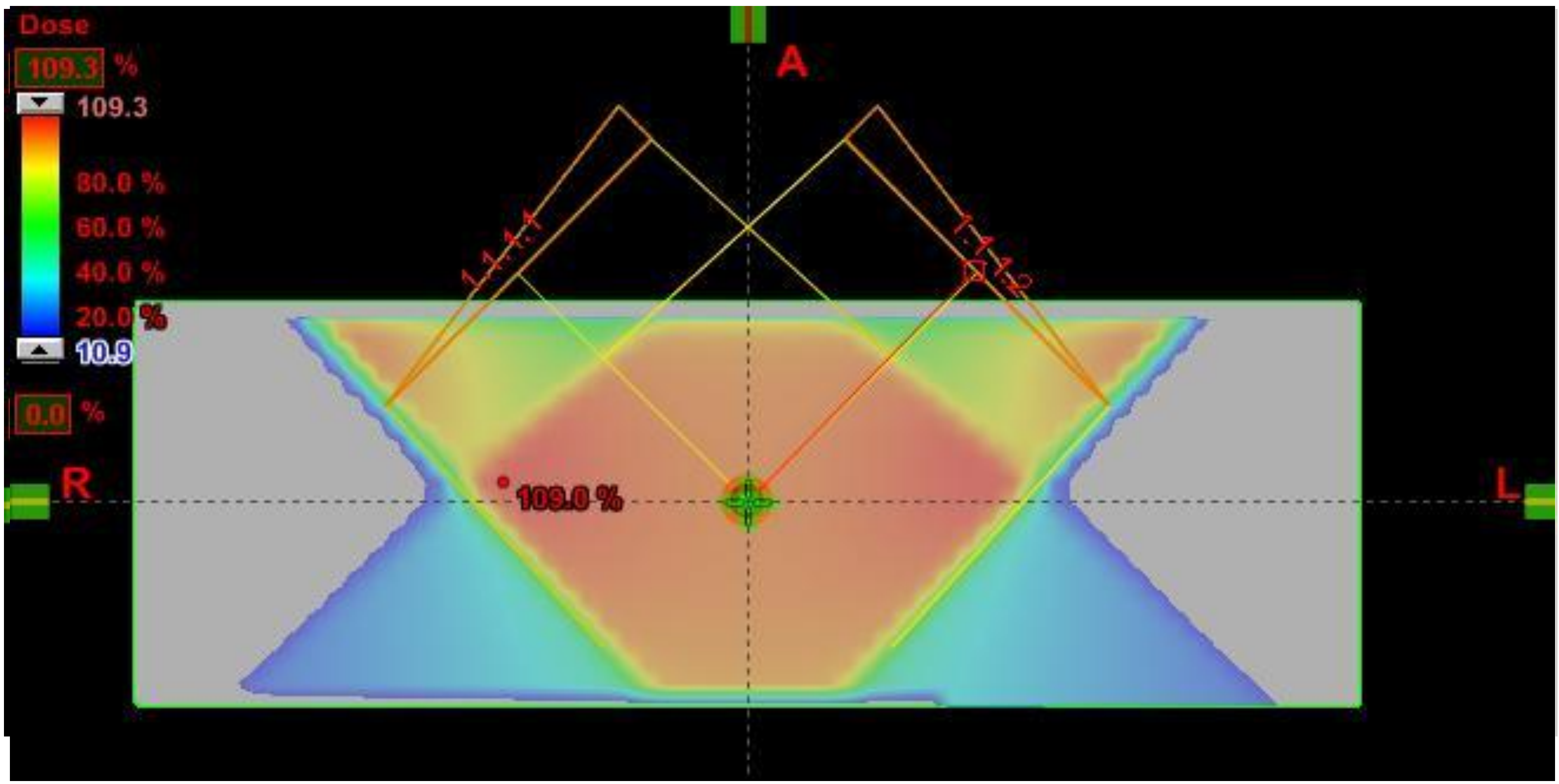
SCULPTING A TREATMENT BEAM: DOSE DISTRIBUTION USING WEDGES

- Standardized linearly varying intensity distribution



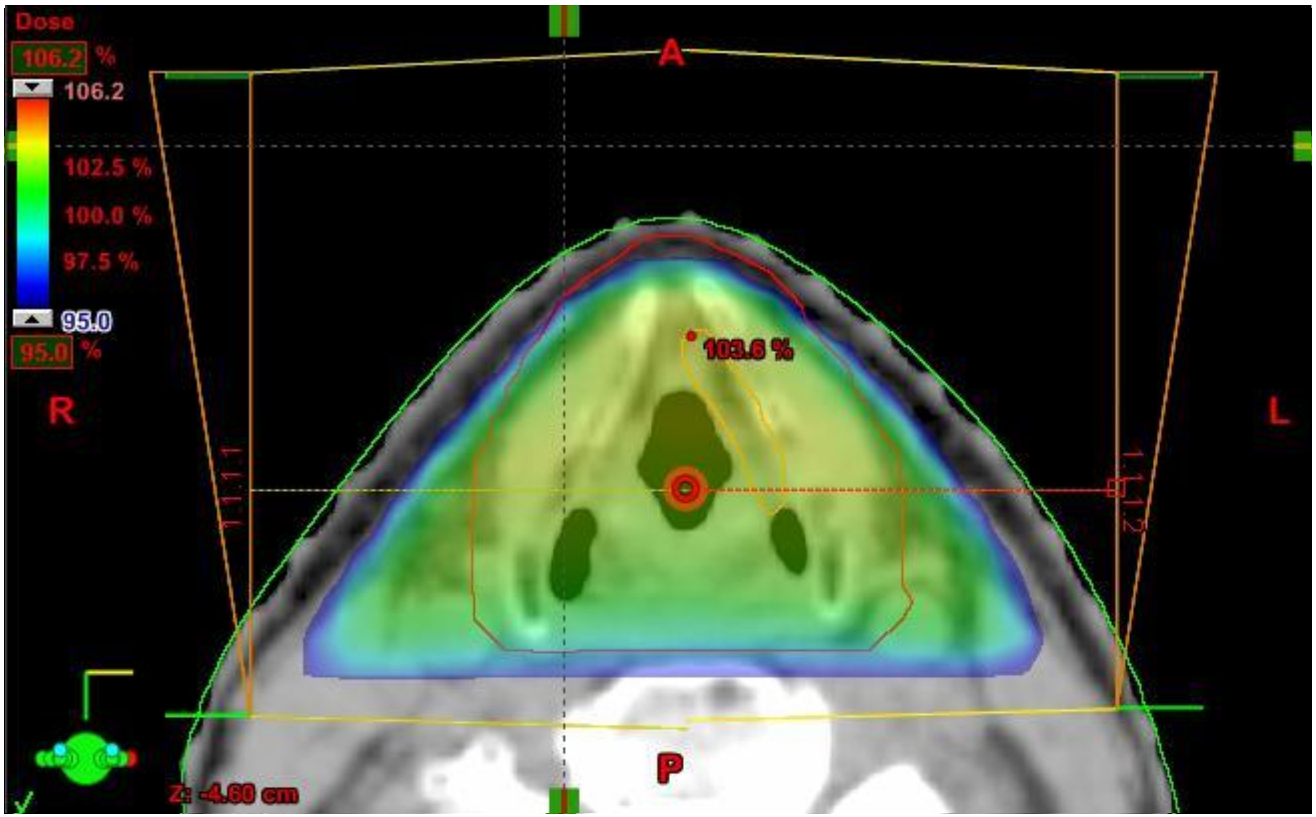
SCULPTING A TREATMENT BEAM: USE OF WEDGES

- used for combining treatment beams:
  e.g. pair of beams at 90° to one another



SCULPTING A TREATMENT BEAM: USE OF WEDGES

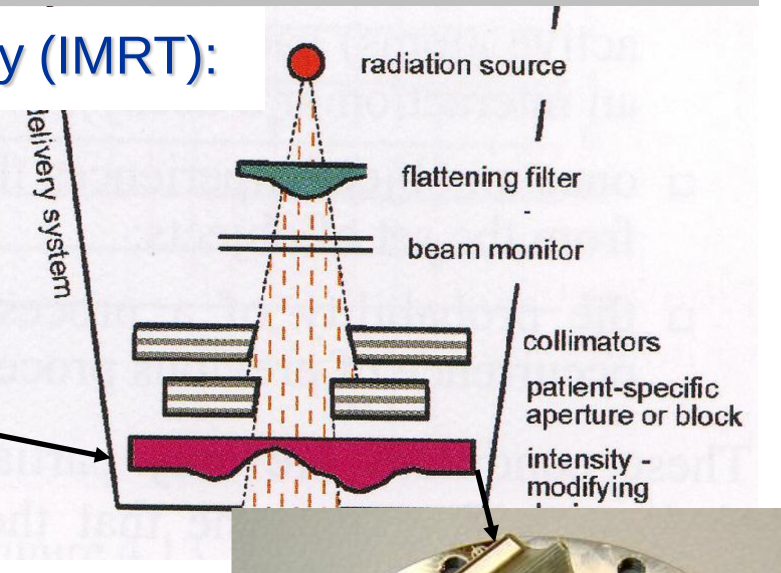
- used for compensating a sloping patient surface



SCULPTING A TREATMENT BEAM: PATIENT-SPECIFIC INTENSITY MODULATION

Intensity-modulated radiation therapy (IMRT):

- Sculpting the dose distribution
- Metallic irregularly formed attenuators



- More common: dynamically modifying the position of each leaf of a MLC and thereby the size and shape of the field during the course of delivery of a beam

How should the shape and intensity profiles of beams be designed?
How do we calculate dose?