Course overview

Monday, 30th September

08:00-09:30 Basic physics	Prof. Tony Lomax
10:00-11:30 Delivery and verification	Dr. Nicolas Perichon
11:30-13:00 Lunch	
13:00-14:30 Imaging	PD Dr. Jean-Francois Germond
15:00-16:30 Beam shaping	Prof. Uwe Schneider

Tuesday, 01st October

08:00-09:30 Treatment planning	Prof. Uwe Schneider
10:00-11:30 TPS evaluation	Prof. Tony Lomax
11:30-13:00 Lunch	
13:00-14:30 Brachytherapy	Dr. Dario Terribilini
15:00-16:30 Radiation protection	Prof. Uwe Schneider
16:30-17:30 Tour of the department	*Optional*

Wednesday, 02nd October

08:00-09:30 Dosimetry	Dr. Jürgen Besserer
10:00-12:00 Special techniques	Prof. Tony Lomax & Prof. Raphael Moeckli

PAUL SCHERRER INSTITUT

Tony Lomax :: Head of Medical Physics :: Paul Scherrer Institute
Department of Physics :: ETH-Zurich

The physics background to radiotherapy

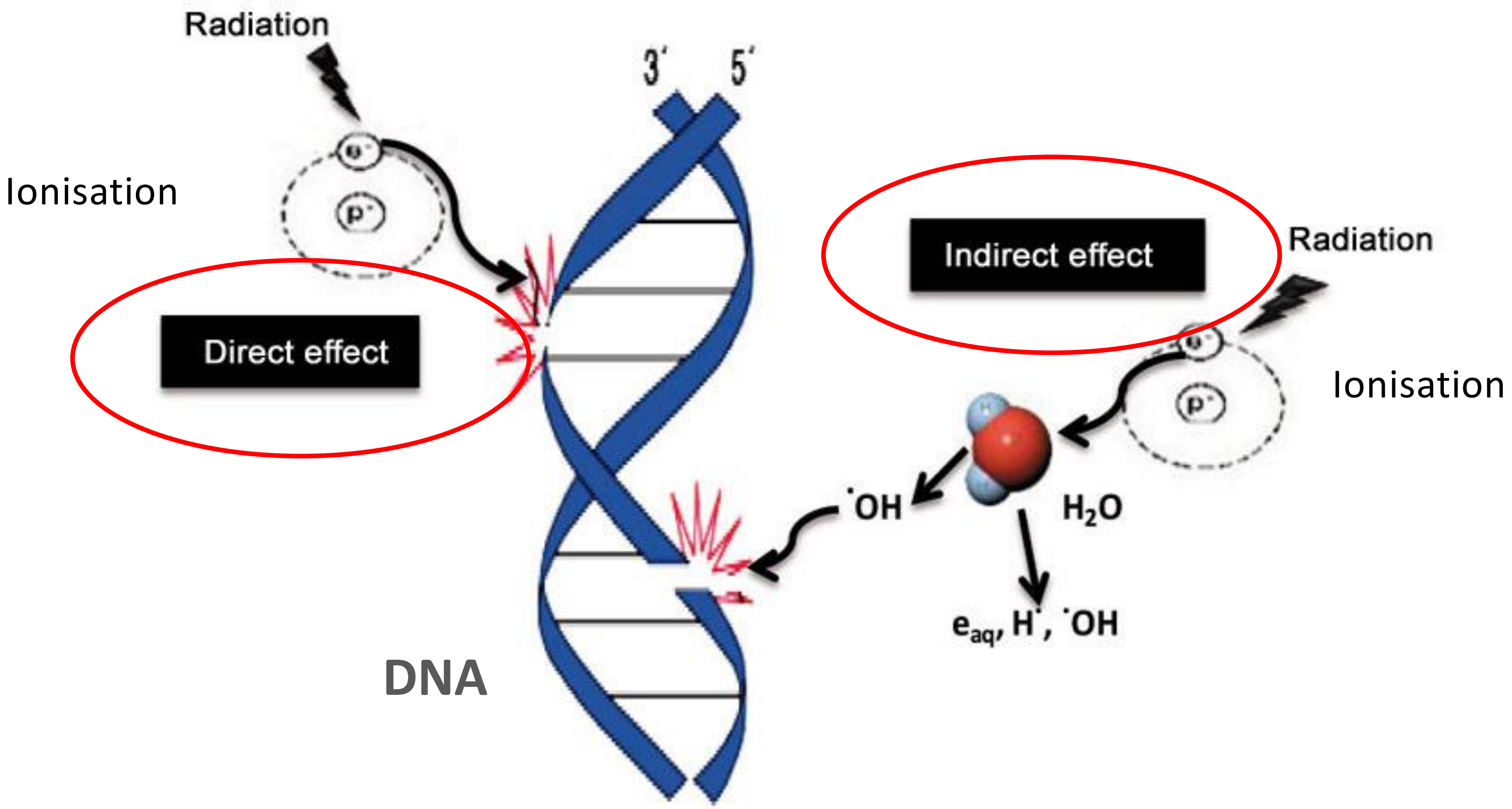
FMH physics training, 30th September 2024

Overview of presentation

1. A brief history of radiotherapy
2. Fundamentals of radioactivity
3. Interactions of radiation with matter
4. The physics of radiotherapy

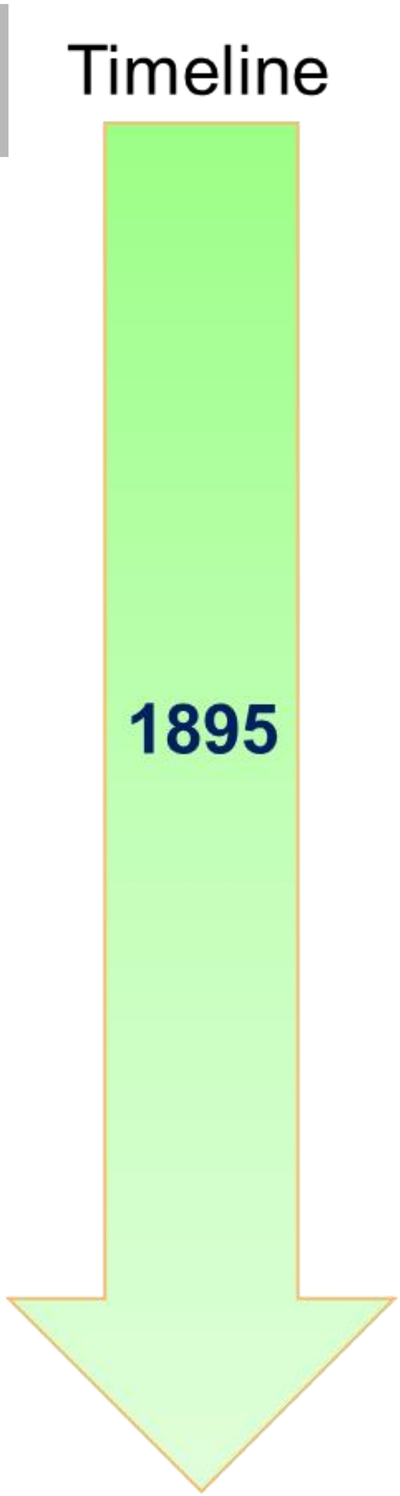
The fundamentals of radiotherapy

Energy deposited by radiation (dose = J/kg or Gray) through ionization can damage DNA and thus sterilise cells



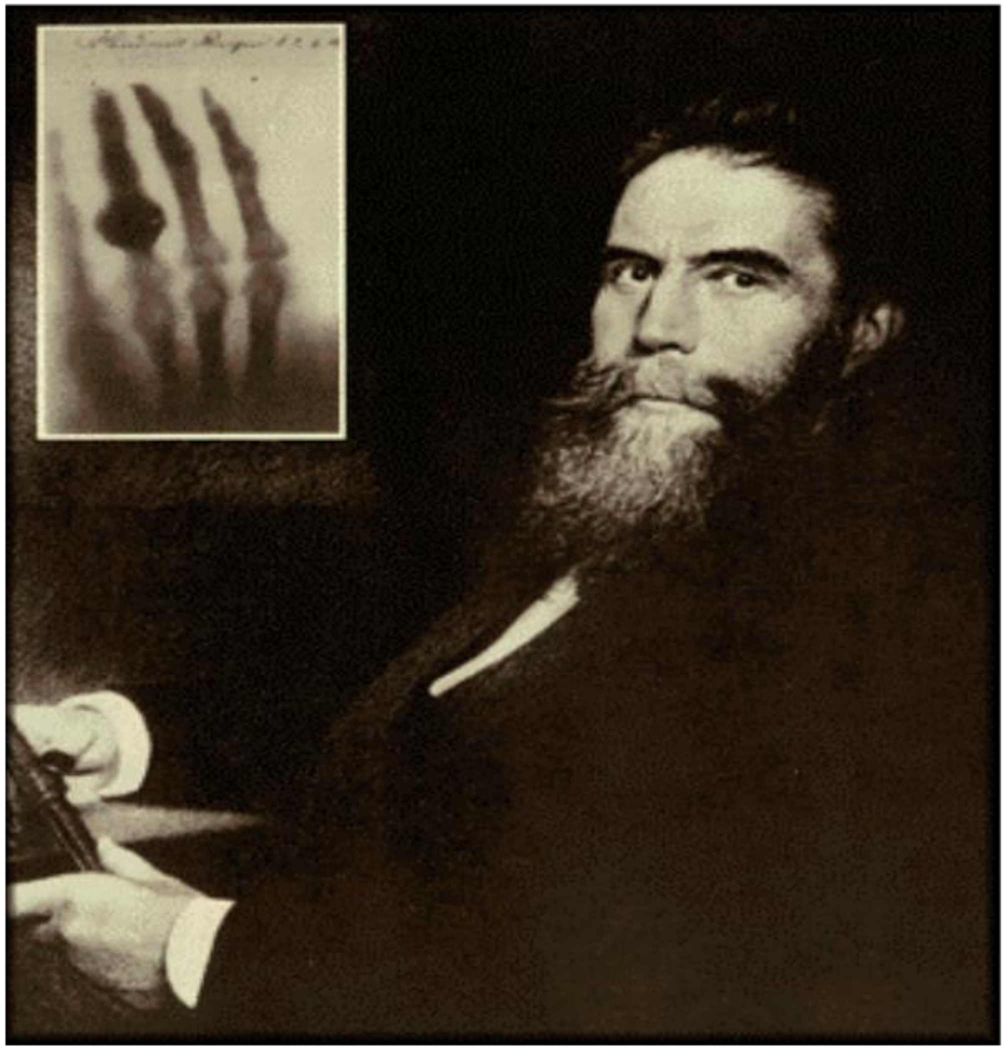
1. A Brief history of radiotherapy

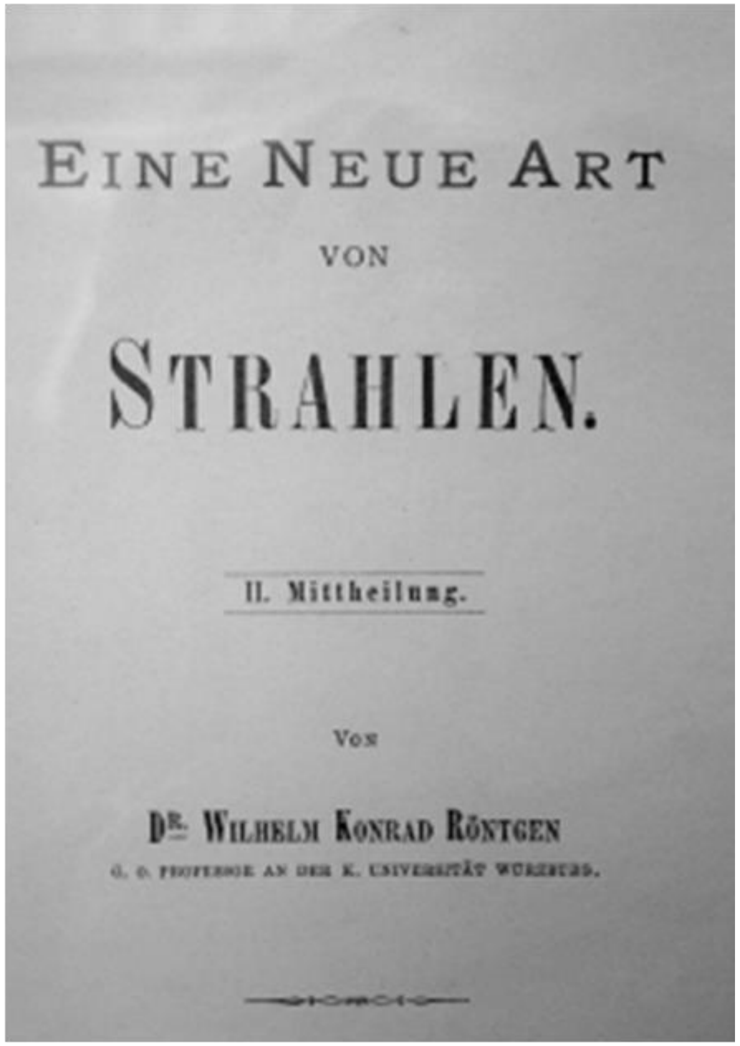
How it all began



Timeline

1895





EINE NEUE ART

VON

STRAHLEN.

II. Mittheilung.

VON

DR. WILHELM KONRAD RÖNTGEN

O. Ö. PROFESSOR AN DER K. UNIVERSITÄT WÜRZBURG.

Wilhelm Roentgen – Discoverer of X-rays on 8th November 1895

1. A Brief history of radiotherapy

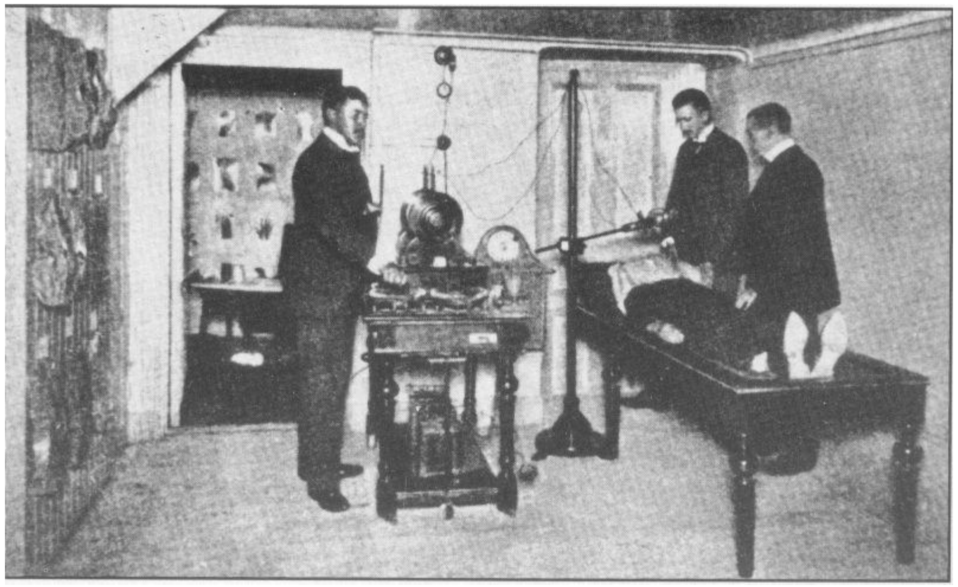
The first treatments

Timeline

1896

Emil Grubbe – The first radiotherapy treatment of a recurrent breast cancer in the last days of January 1896, just weeks after the announcement of Roentgen's discovery of X-rays

1899

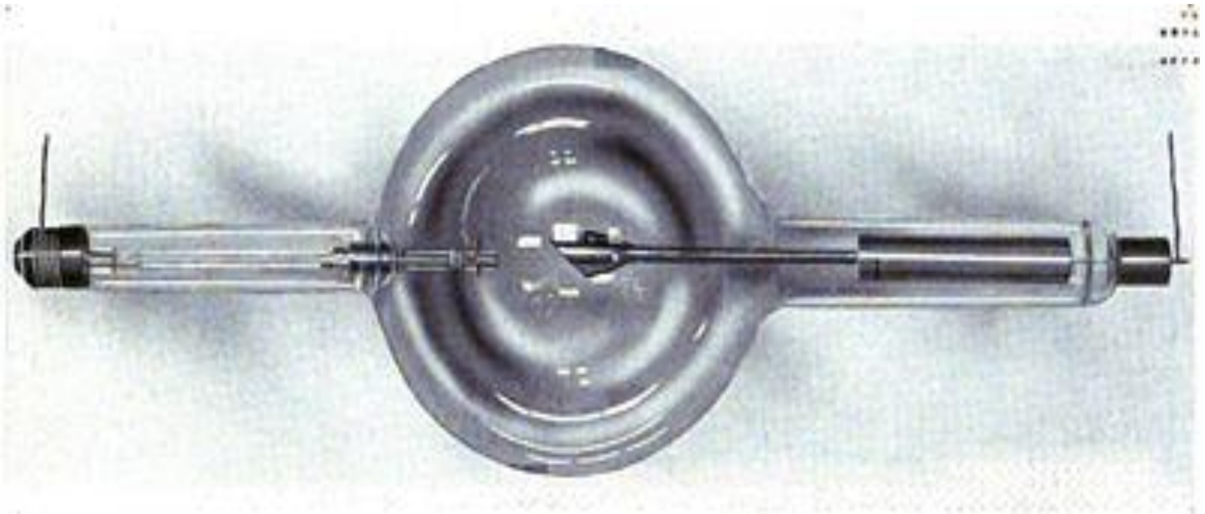


Thor Stenbeck - A first(?) successful treatment of a basal-cell skin carcinoma of the nose The patient was living and well 30 years later.

Increasing the energy (1)

Timeline

1912

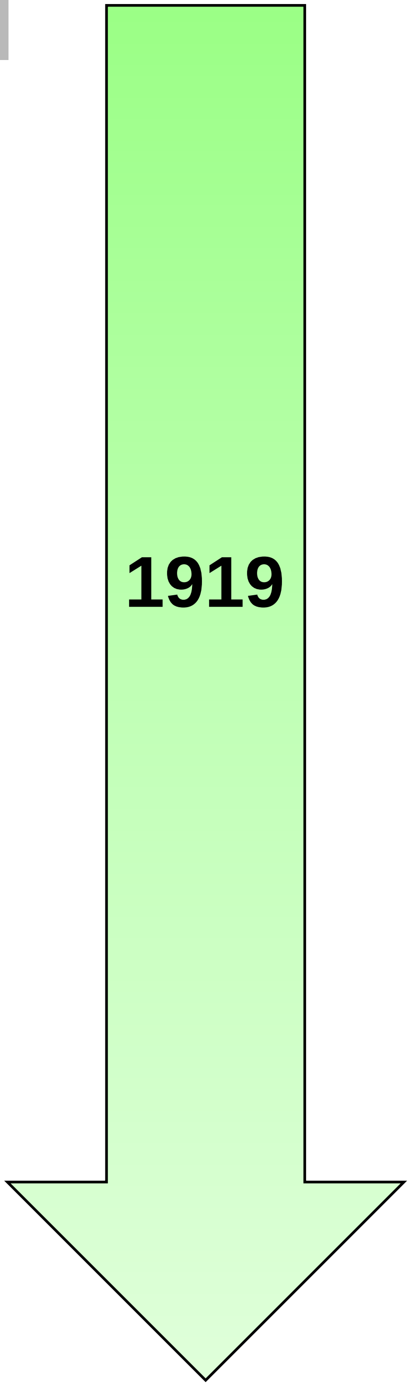


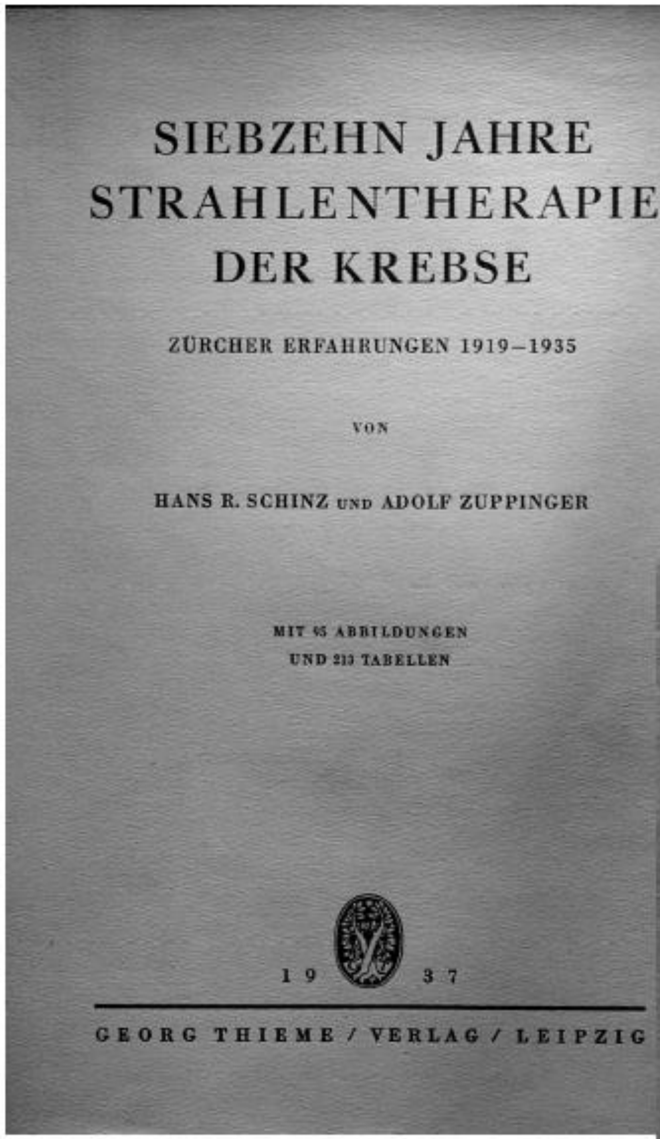
William Coolidge – Inventor of the X-ray tube. The heated cathode is on the left, and the anode is right. The X-rays are emitted downwards.

1. A Brief history of radiotherapy

The beginning of radiotherapy in Switzerland

Timeline





SIEBZEHN JAHRE
STRAHLENTHERAPIE
DER KREBSE

ZÜRCHER ERFAHRUNGEN 1919–1935

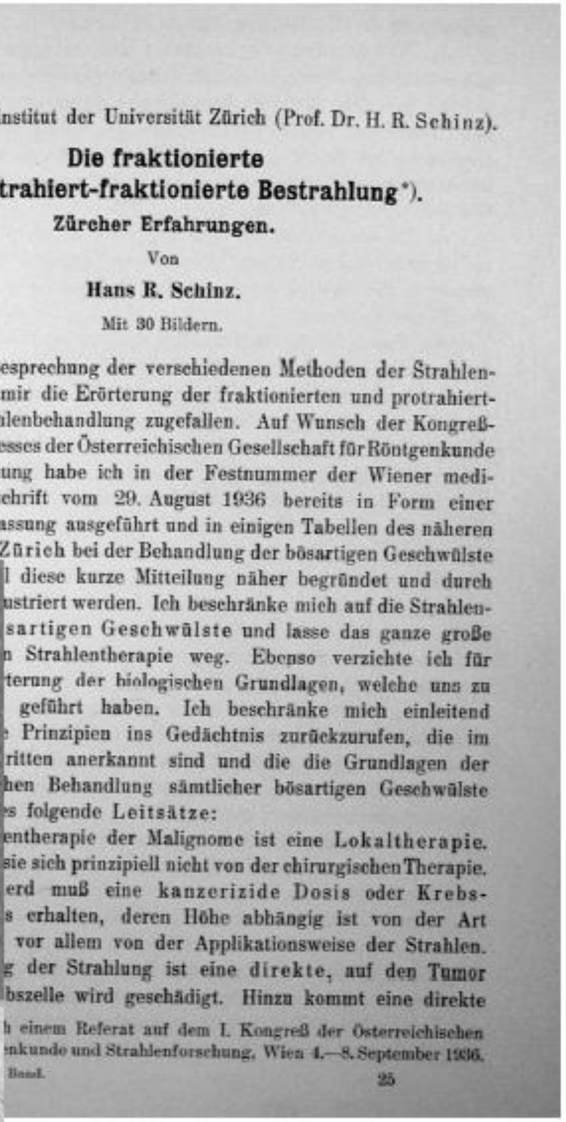
VON

HANS R. SCHINZ UND ADOLF ZUPPINGER

MIT 95 ABBILDUNGEN
UND 213 TABELLEN

1 9 3 7

GEORG THIEME / VERLAG / LEIPZIG



Aus dem Röntgeninstitut der Universität Zürich (Prof. Dr. H. R. Schinz).

**Die fraktionierte
und protrahiert-fraktionierte Bestrahlung***).

Zürcher Erfahrungen.

Von

Hans R. Schinz.

Mit 30 Bildern.

Im Rahmen der Besprechung der verschiedenen Methoden der Strahlenbehandlung ist mir die Erörterung der fraktionierten und protrahiert-fraktionierten Strahlenbehandlung zugefallen. Auf Wunsch der Kongreßleitung des I. Kongresses der Österreichischen Gesellschaft für Röntgenkunde und Strahlenforschung habe ich in der Festnummer der Wiener medizinischen Wochenschrift vom 29. August 1936 bereits in Form einer kurzen Zusammenfassung ausgeführt und in einigen Tabellen des näheren erörtert, wie wir in Zürich bei der Behandlung der bösartigen Geschwülste
l diese kurze Mitteilung näher begründet und durch
ustriert werden. Ich beschränke mich auf die Strahlen-
sartigen Geschwülste und lasse das ganze große
n Strahlentherapie weg. Ebenso verzichte ich für
terung der biologischen Grundlagen, welche uns zu
geführt haben. Ich beschränke mich einleitend
Prinzipien ins Gedächtnis zurückzurufen, die im
ritten anerkannt sind und die die Grundlagen der
hen Behandlung sämtlicher bösartigen Geschwülste
s folgende Leitsätze:
entherapie der Malignome ist eine Lokaltherapie.
sie sich prinzipiell nicht von der chirurgischen Therapie.
erd muß eine kanzerizide Dosis oder Krebs-
s erhalten, deren Höhe abhängig ist von der Art
vor allem von der Applikationsweise der Strahlen.
g der Strahlung ist eine direkte, auf den Tumor
bszelle wird geschädigt. Hinzu kommt eine direkte

h einem Referat auf dem I. Kongreß der Österreichischen
nkunde und Strahlenforschung, Wien 4.–8. September 1936.
Band.
25

Adolf Zuppinger – An early pioneer of radiotherapy in Switzerland

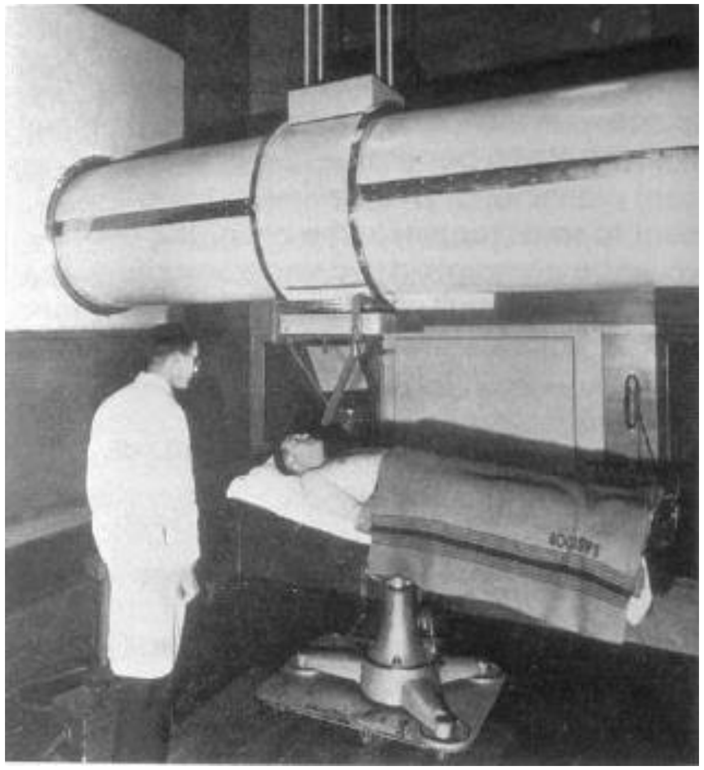
Increasing the energy (2)

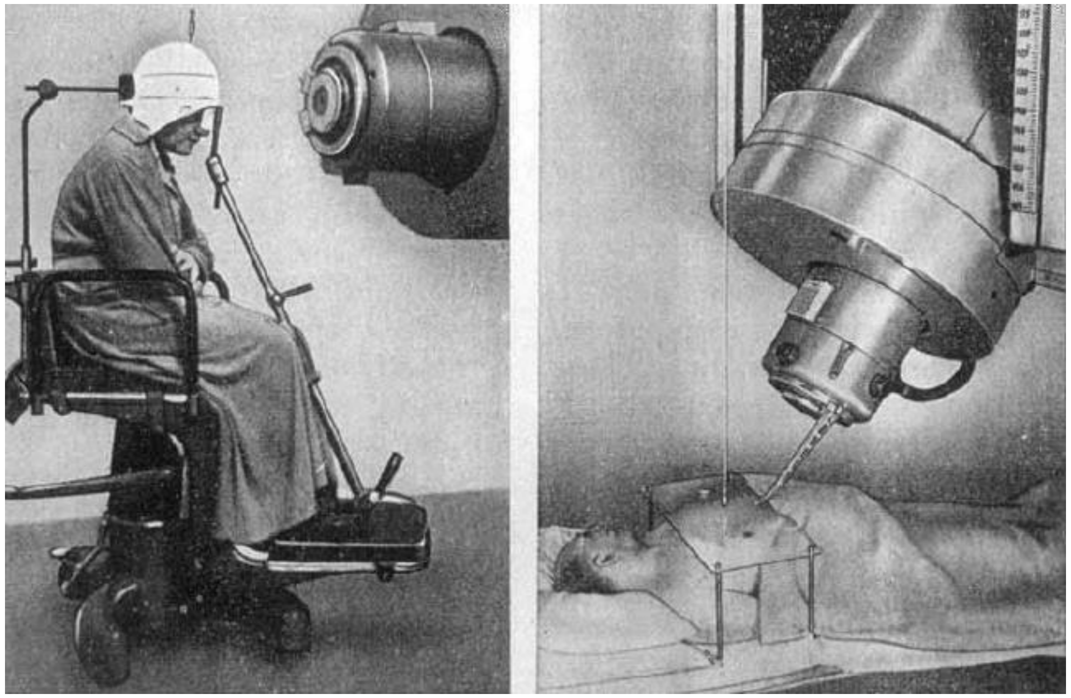
Timeline

1937

Ralph Phillips and **George Innes**

- Development of 1 MeV X-ray tube on rotating gantry at St. Bartholomew's, London.





Robert van der Graaf – Inventor of the van der Graaf generator. Shown is the 2MV van der Graaf unit at the Royal Marsden Hospital in London

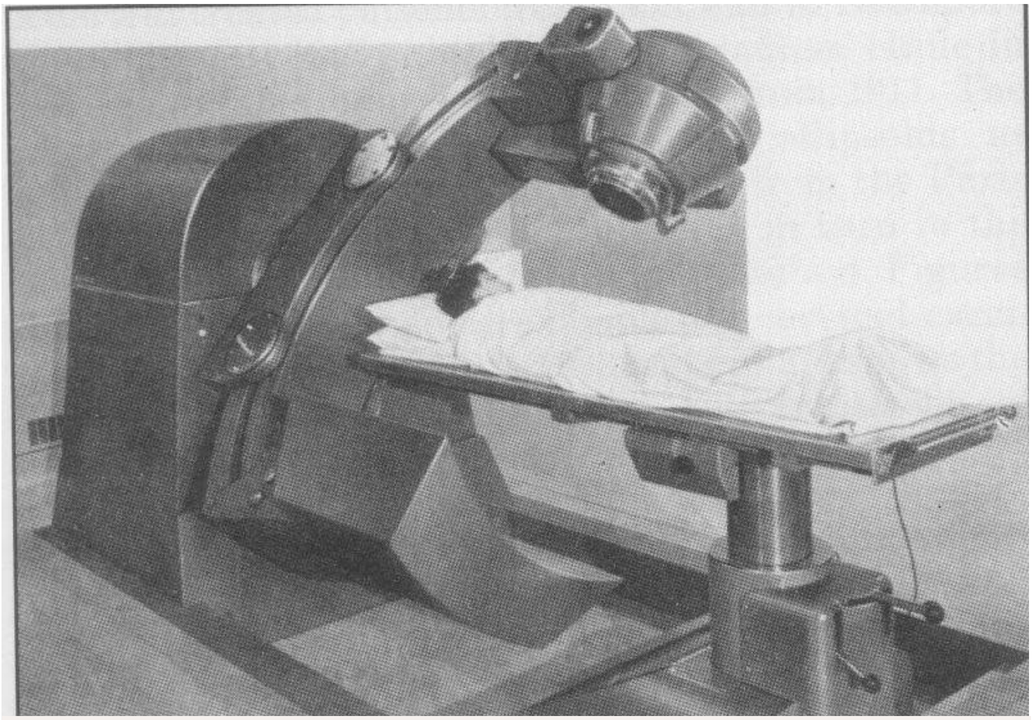
1. A Brief history of radiotherapy

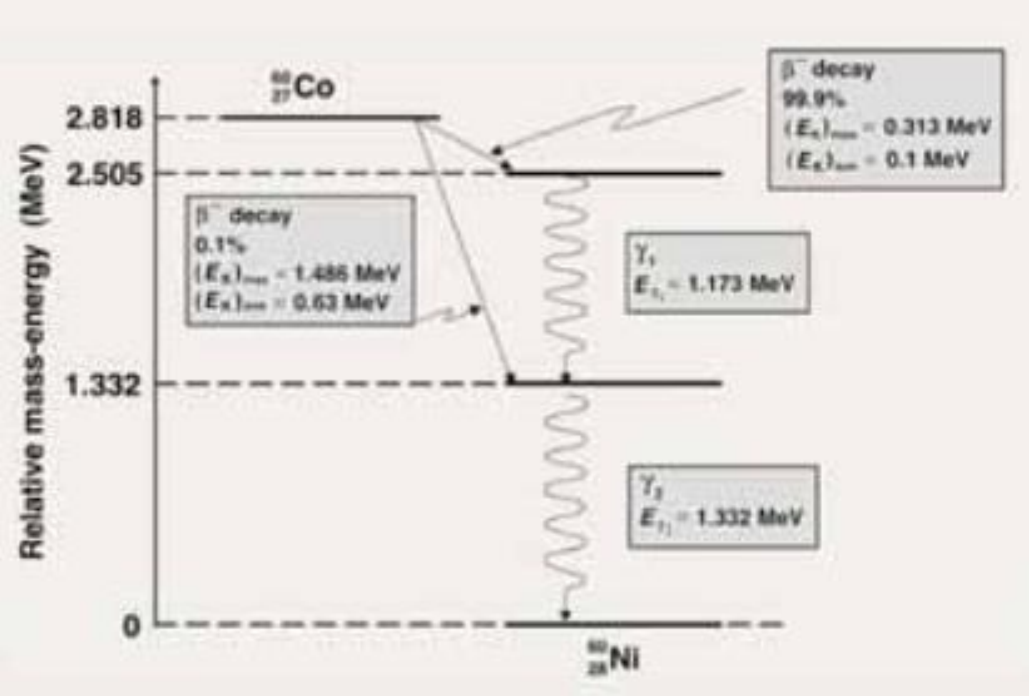
Increasing the energy (3)

Timeline

1952

Harold Johns –
Inventor of the Cobalt-60 teletherapy machine for radiotherapy





Increasing the energy (4)

Timeline

1953

The Mullard (Philips) 4 MV double gantry linac. First installed at Newcastle Hospital, UK

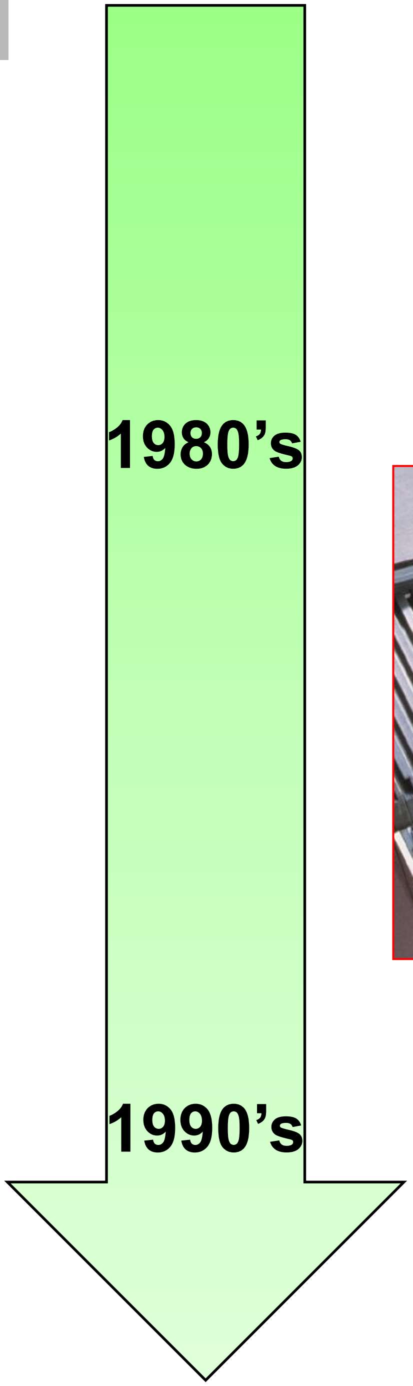
1957

Stanford USA - First application of a 6MV linear accelerator (developed by **Ising** and **Wideroe** in the late 1920’s) in radiotherapy

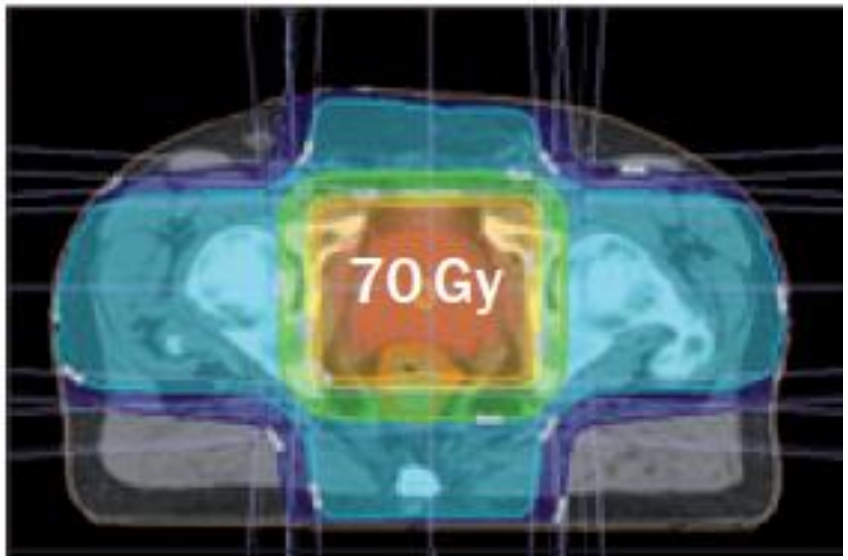
1. A Brief history of radiotherapy

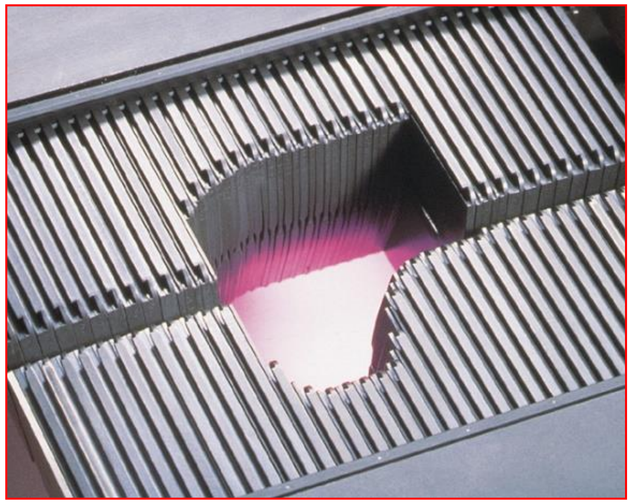
The power of the computer

Timeline



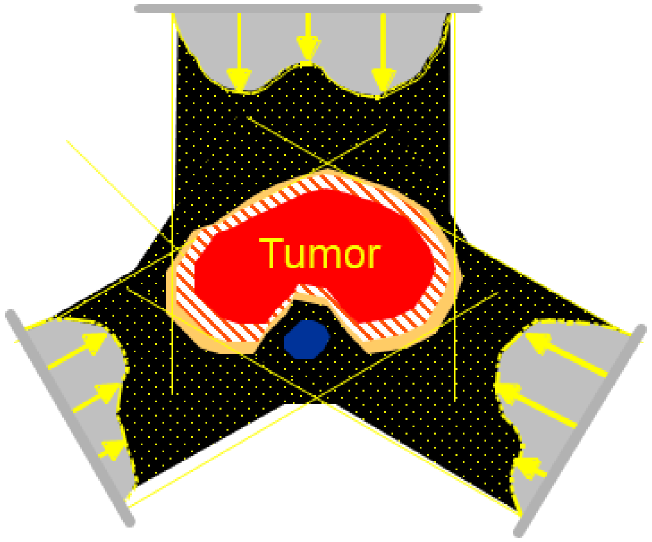
3D based computer based treatment simulations (3D treatment planning)





The multi-leaf collimator – computer controlled collimation of treatment fields

Computer assisted optimization of treatments – Intensity Modulated Radiotherapy (IMRT)

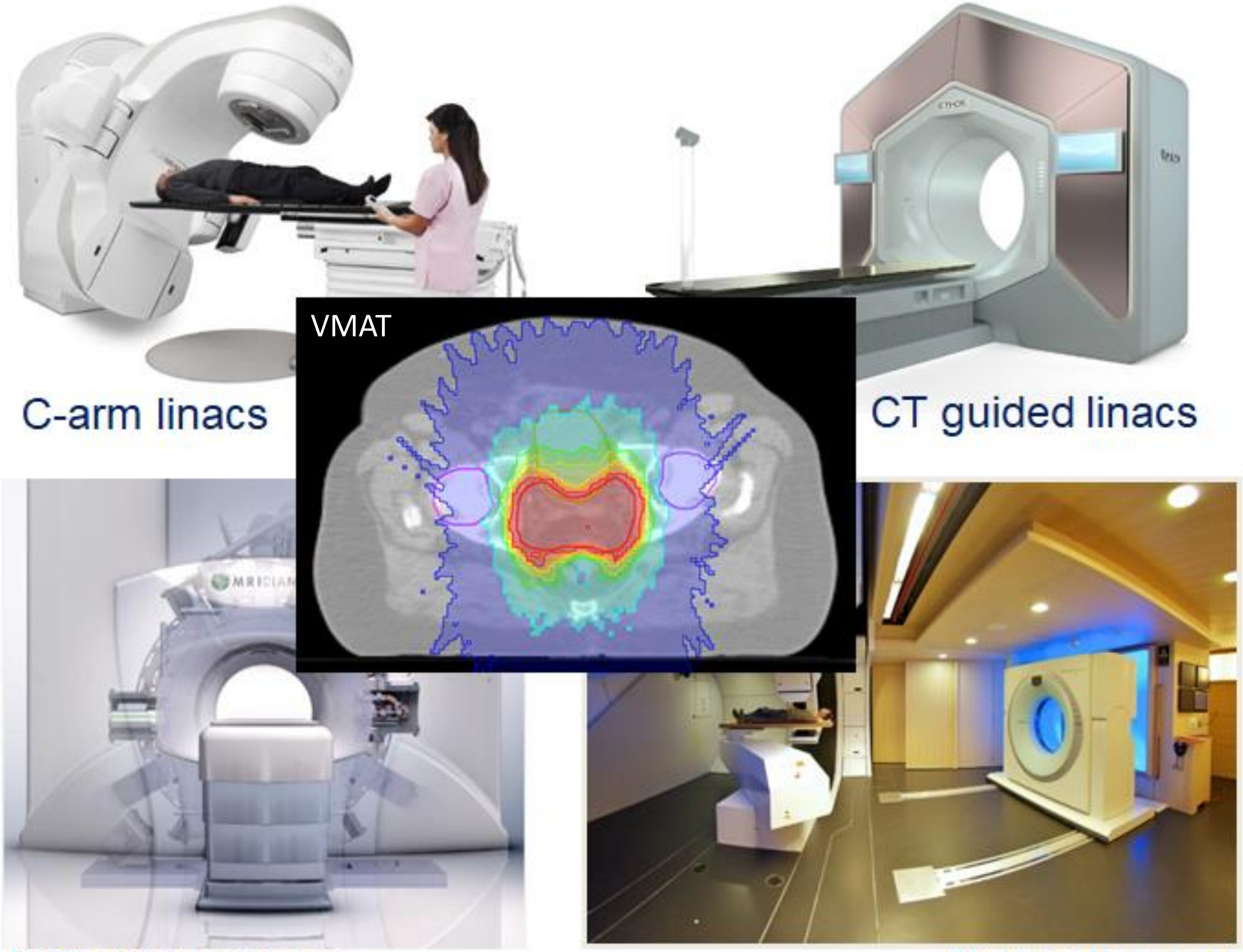


1. A Brief history of radiotherapy

Where we are now

Timeline

2020's



C-arm linacs

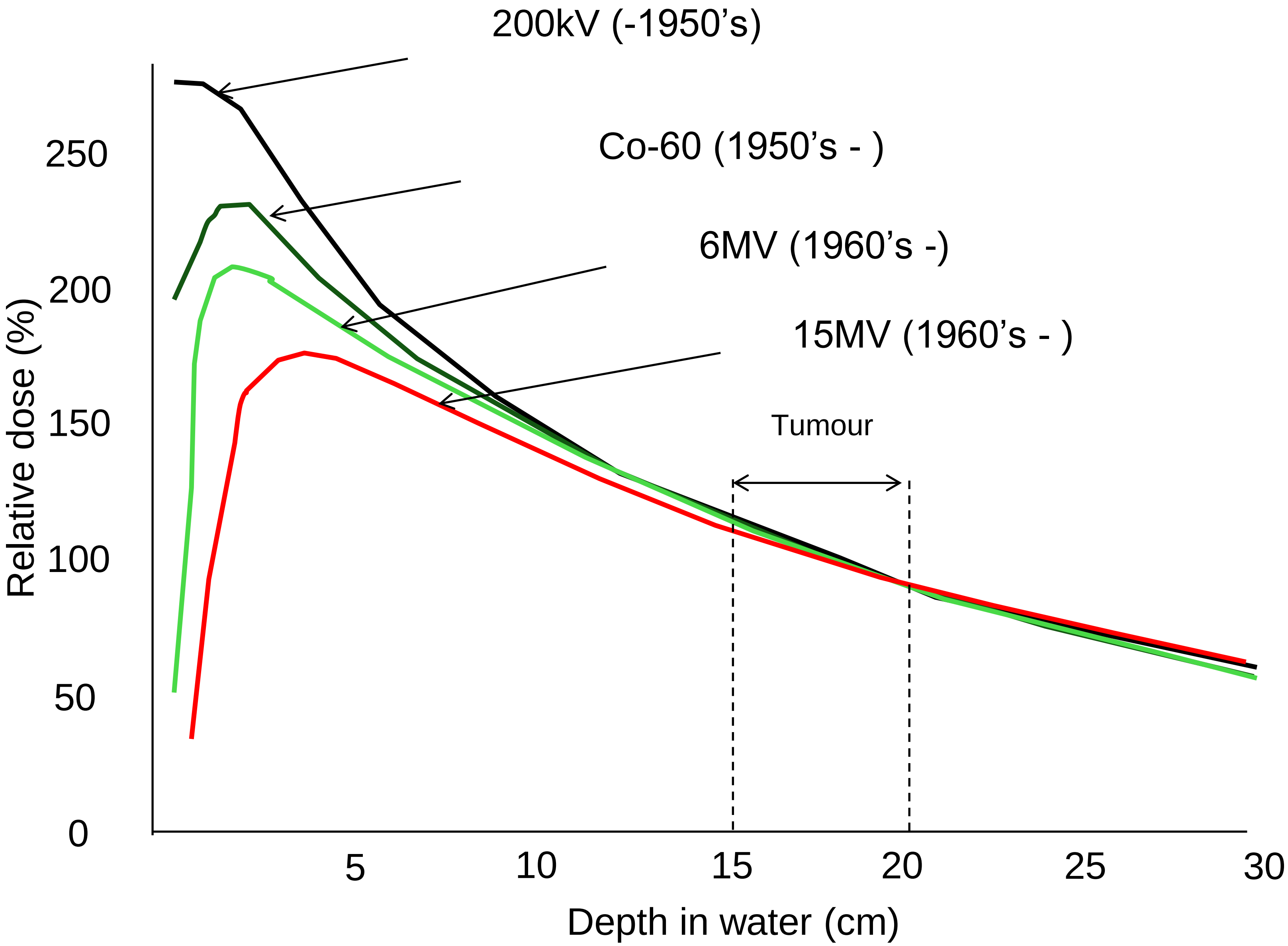
CT guided linacs

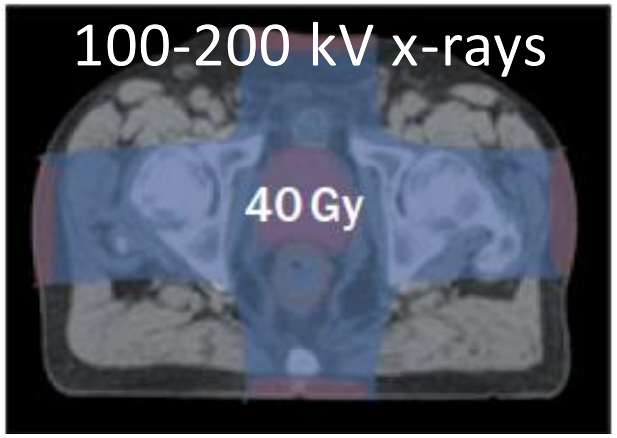
MR guided linacs

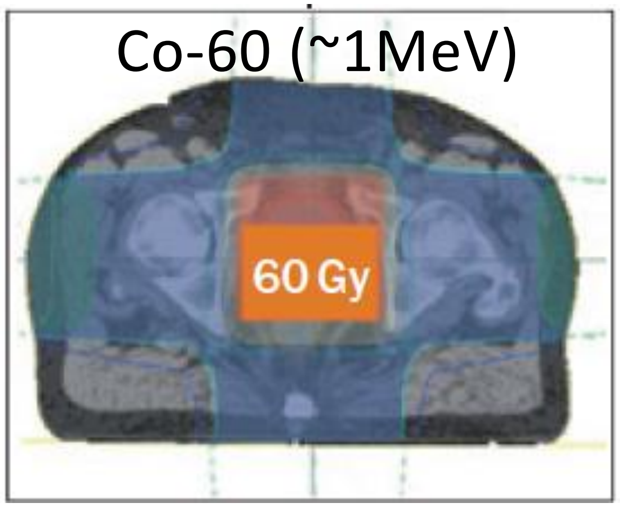
Proton therapy

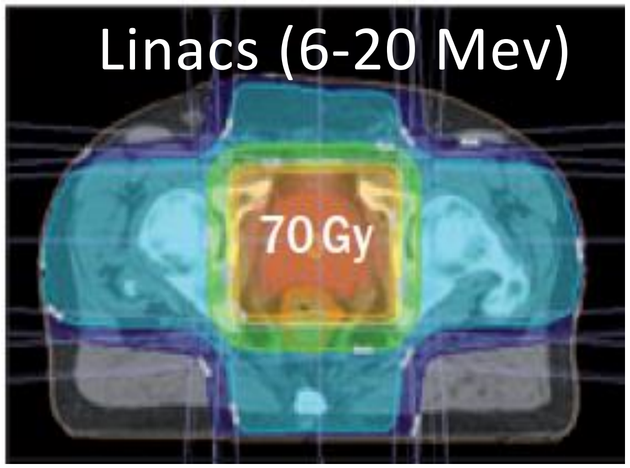
1. A Brief history of radiotherapy

The role of physics









Overview of presentation

1. A brief history of radiotherapy
2. Fundamentals of radioactivity
3. Interactions of radiation with matter
4. The physics of radiotherapy

Classification of Radiation

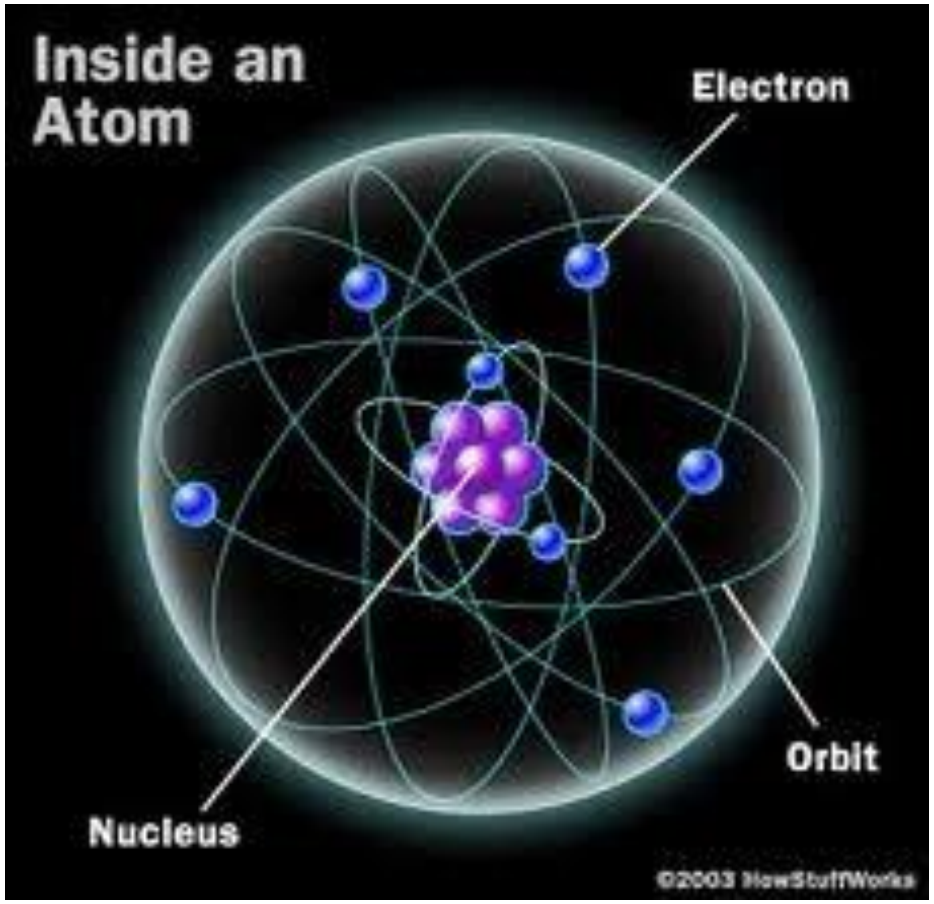
Type of effect

- Non-ionising radiation (E.g. RF, microwaves etc.)
- Ionising radiation:
  - Directly ionizing (charged particles: electrons, protons, alpha-particles etc.)
  - Indirectly ionizing (uncharged particles: X-rays, gamma rays, neutrons)

Types of ionising radiation

- Particle radiation
  (solid projectiles: electrons, protons, alpha-particles, neutrons etc.)
- Electromagnetic radiation: photons (gammas, X-ray, ...)

Microscopic View - Description of matter



Particles making up an *stable* **atom**:

- Z Protons
- N Neutrons
- Z Electrons

$$^{A}_{Z}X_{N}$$

Atomic weight: $\boldsymbol{A} = \boldsymbol{Z} + \boldsymbol{N}$

Protons and neutrons are known as nucleons

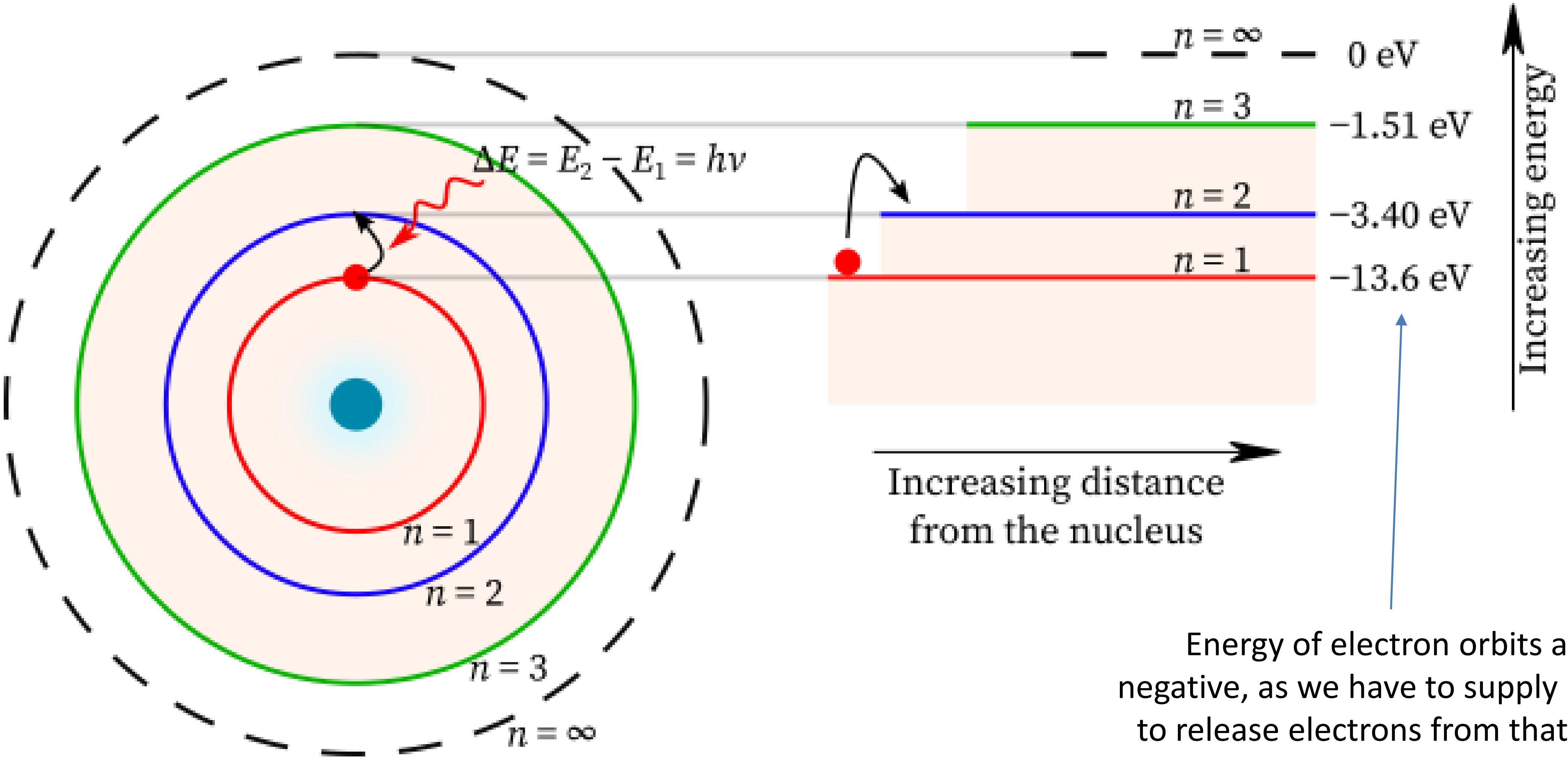
Models of the Atom

Bohr‘s Model of the Hydrogen Atom

- Combination of Rutherford‘s model and Planck‘s Idea of quantitized nature of radiation processes
- Electrons populate orbits without loosing energy despite being constantly accelerated
- The angular momentum of electrons in an allowed orbit is quantitized (=> ‘Quantum Physics’)
- Emission of radiation occurs only when an electron transits from one orbit to another

Models of the Atom

E.g. Energy levels of Bohr‘s Model

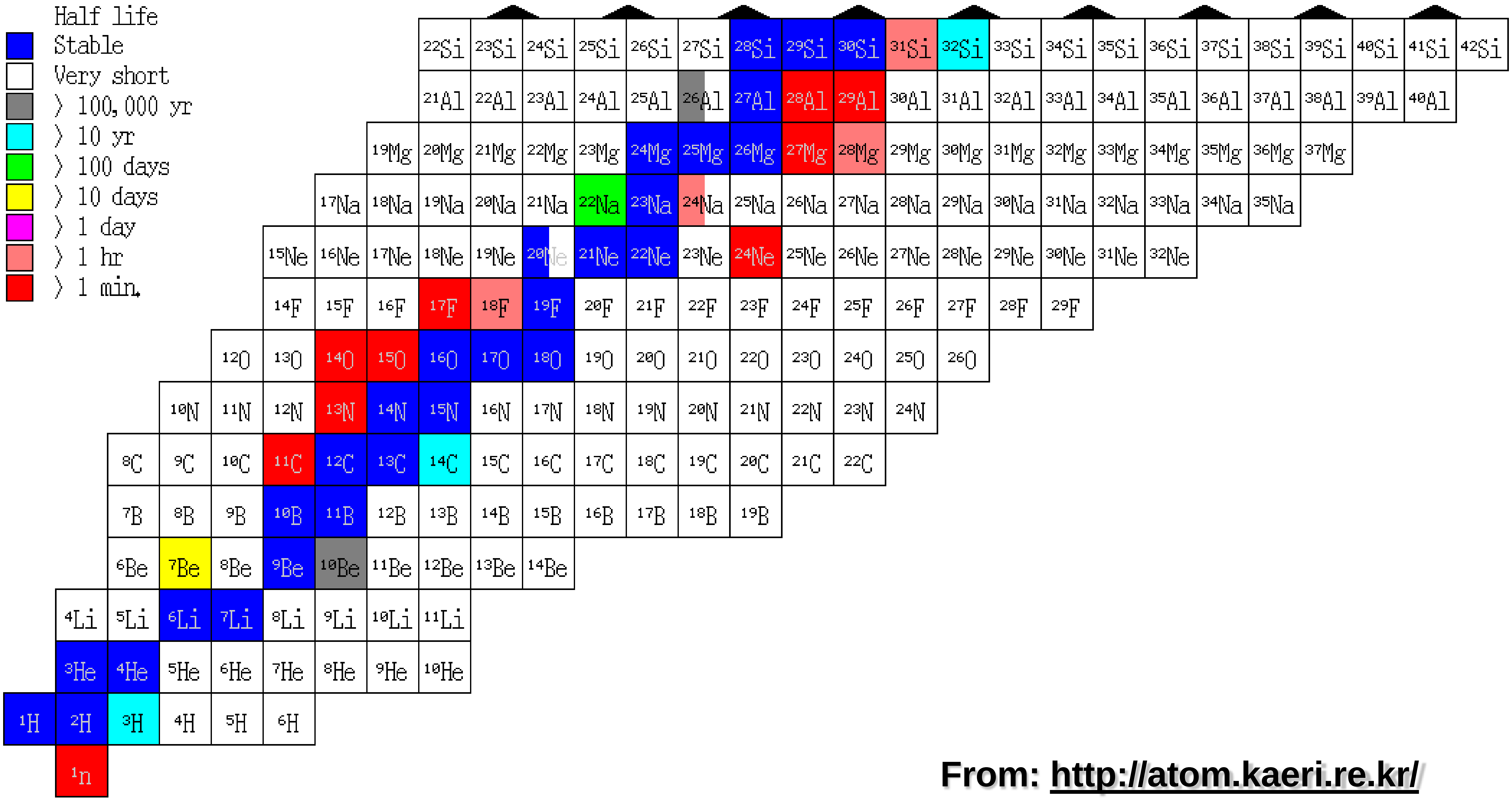


Energy of electron orbits are negative, as we have to supply energy to release electrons from that orbit

Hydrogen atom with its energy levels

https://chemistrygod.com/bohr-atomic-model

Radiation sources – Radioisotopes



Half life
🟦 Stable
⬜ Very short
▩ > 100,000 yr
🟦 > 10 yr
🟩 > 100 days
🟨 > 10 days
🟪 > 1 day
🟧 > 1 hr
🟥 > 1 min.

^{22}Si ^{23}Si ^{24}Si ^{25}Si ^{26}Si ^{27}Si ^{28}Si ^{29}Si ^{30}Si ^{31}Si ^{32}Si ^{33}Si ^{34}Si ^{35}Si ^{36}Si ^{37}Si ^{38}Si ^{39}Si ^{40}Si ^{41}Si ^{42}Si

^{21}Al ^{22}Al ^{23}Al ^{24}Al ^{25}Al ^{26}Al ^{27}Al ^{28}Al ^{29}Al ^{30}Al ^{31}Al ^{32}Al ^{33}Al ^{34}Al ^{35}Al ^{36}Al ^{37}Al ^{38}Al ^{39}Al ^{40}Al

^{19}Mg ^{20}Mg ^{21}Mg ^{22}Mg ^{23}Mg ^{24}Mg ^{25}Mg ^{26}Mg ^{27}Mg ^{28}Mg ^{29}Mg ^{30}Mg ^{31}Mg ^{32}Mg ^{33}Mg ^{34}Mg ^{35}Mg ^{36}Mg ^{37}Mg

^{17}Na ^{18}Na ^{19}Na ^{20}Na ^{21}Na ^{22}Na ^{23}Na ^{24}Na ^{25}Na ^{26}Na ^{27}Na ^{28}Na ^{29}Na ^{30}Na ^{31}Na ^{32}Na ^{33}Na ^{34}Na ^{35}Na

^{15}Ne ^{16}Ne ^{17}Ne ^{18}Ne ^{19}Ne ^{20}Ne ^{21}Ne ^{22}Ne ^{23}Ne ^{24}Ne ^{25}Ne ^{26}Ne ^{27}Ne ^{28}Ne ^{29}Ne ^{30}Ne ^{31}Ne ^{32}Ne

^{14}F ^{15}F ^{16}F ^{17}F ^{18}F ^{19}F ^{20}F ^{21}F ^{22}F ^{23}F ^{24}F ^{25}F ^{26}F ^{27}F ^{28}F ^{29}F

^{12}O ^{13}O ^{14}O ^{15}O ^{16}O ^{17}O ^{18}O ^{19}O ^{20}O ^{21}O ^{22}O ^{23}O ^{24}O ^{25}O ^{26}O

^{10}N ^{11}N ^{12}N ^{13}N ^{14}N ^{15}N ^{16}N ^{17}N ^{18}N ^{19}N ^{20}N ^{21}N ^{22}N ^{23}N ^{24}N

^{8}C ^{9}C ^{10}C ^{11}C ^{12}C ^{13}C ^{14}C ^{15}C ^{16}C ^{17}C ^{18}C ^{19}C ^{20}C ^{21}C ^{22}C

^{7}B ^{8}B ^{9}B ^{10}B ^{11}B ^{12}B ^{13}B ^{14}B ^{15}B ^{16}B ^{17}B ^{18}B ^{19}B

^{6}Be ^{7}Be ^{8}Be ^{9}Be ^{10}Be ^{11}Be ^{12}Be ^{13}Be ^{14}Be

^{4}Li ^{5}Li ^{6}Li ^{7}Li ^{8}Li ^{9}Li ^{10}Li ^{11}Li

^{3}He ^{4}He ^{5}He ^{6}He ^{7}He ^{8}He ^{9}He ^{10}He

^{1}H ^{2}H ^{3}H ^{4}H ^{5}H ^{6}H

^{1}n

From: http://atom.kaeri.re.kr/

Radiation sources – Radioisotopes

Examples of radioactive decay mechanisms

β^- Decay

The spontaneous decay of a neutron into a proton and an electron (+ an anti-neutrino!)

$$n \Rightarrow p + e^- + \bar{\upsilon}$$

$$ {}^{A}_{Z}X \Rightarrow {}^{A}_{Z+1}Y + e^- + \bar{\upsilon}$$

β^+ Decay

The spontaneous decay of a proton into a neutron and a positron (+ a neutrino!)

$$p \Rightarrow n + e^+ + \upsilon$$

$$ {}^{A}_{Z}X \Rightarrow {}^{A}_{Z-1}Y + e^+ + \upsilon$$

α Decay

The spontaneous emission from a high-Z nucleus of an alpha particle

$$ {}^{A}_{Z}X \Rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$$

Radioactive decay

Quantity/ Unit:

(Radio)-Activity *A*	1 (event) / s	Bq

Decay results in a decrease of radioactivity within the sample

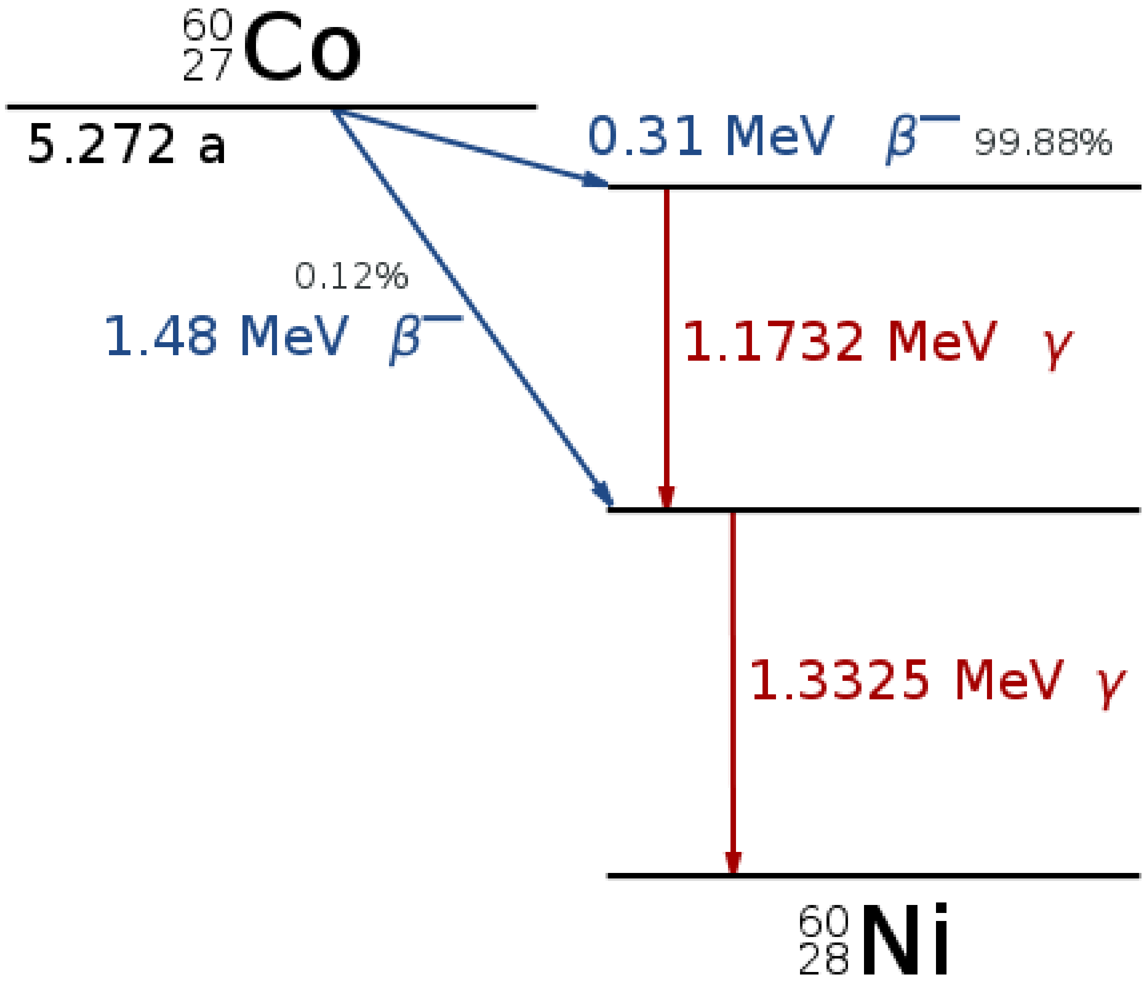
$$A = \mathrm{A}_0 \cdot e^{-\lambda \cdot t}$$

$$\frac{\mathrm{A}_0}{2} = \mathrm{A}_0 \cdot e^{-\lambda \cdot T_{1/2}} \Longrightarrow \lambda = \frac{\ln 2}{T_{1/2}}$$

Radiation sources – Radio-isotopes

E.g. The decay scheme of Co-60

The most important radioisotope for radiotherapy…

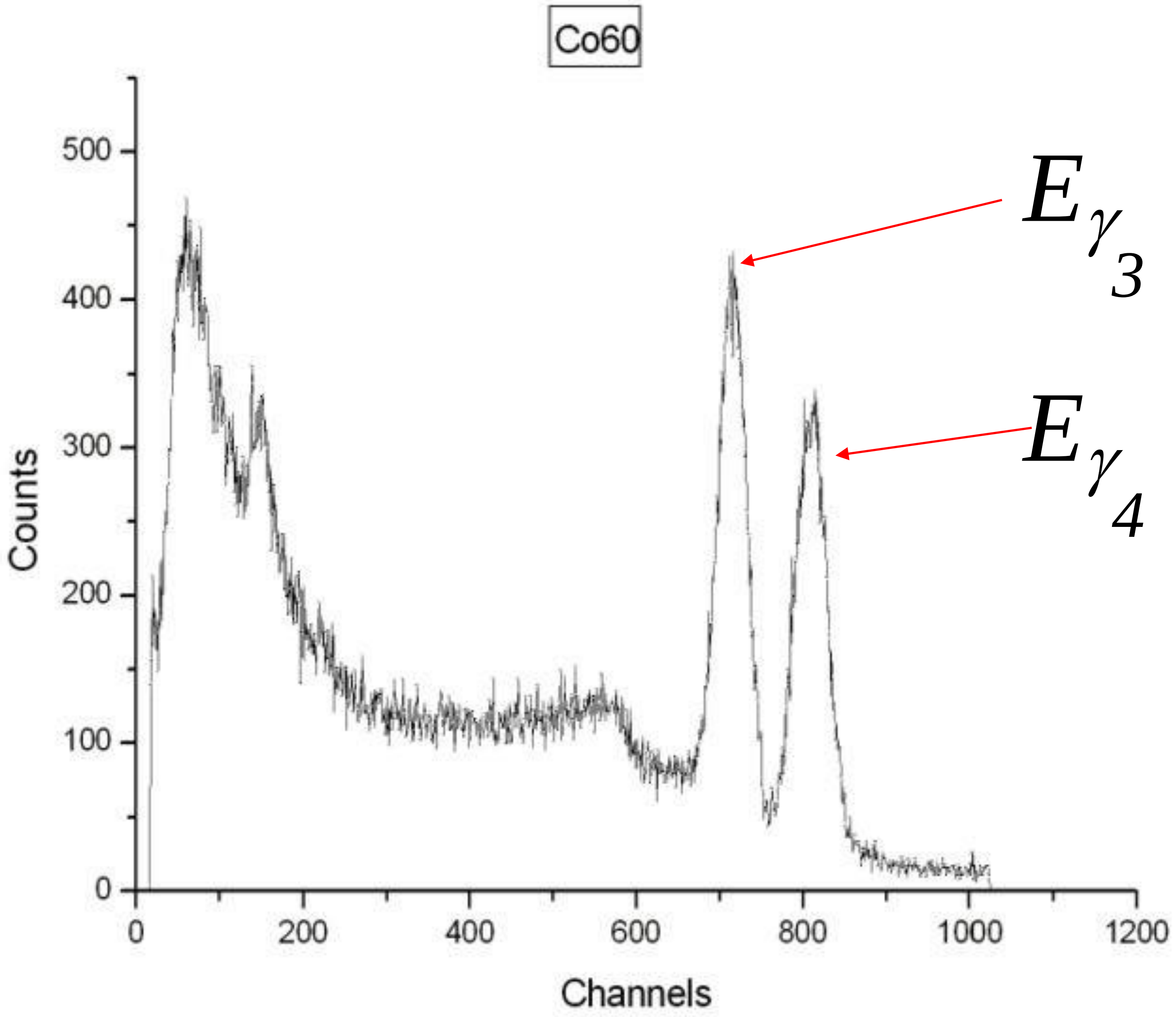


- β^- decays which leaves the nucleus in an excited state
- Nucleus then ‘relaxes’to the final decay product (60-NI) through two stages
- For first ‘relaxation’ a photon of 1.17MeV is emitted
- For the second a photon of 1.33 MeV is emitted

From: http://en.wikipedia.org/wiki/File:Cobalt-60_Decay_Scheme.svg

Radiation sources – Radio-isotopes

^{60}Co-Gamma spectrum



$E_{\gamma_3} = 1.17$ MeV

$E_{\gamma_4} = 1.33$ MeV

From:http://de.wikipedia.org/wiki/Gammaspektroskopie

Overview of presentation

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3. Interactions of radiation with matter

Electrons

Electron-matter interactions

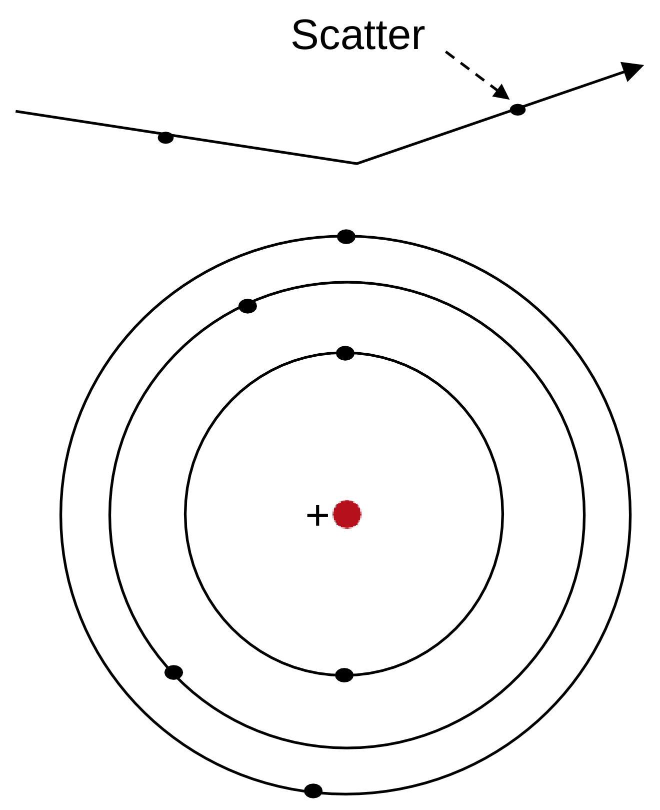
Principle interactions of *charged* particles

- Interaction with shell electrons
  - Elastic scattering
  - Excitation
  - Direct ionisation
- Interactions with nuclei
  - Elastic scattering
  - Bremstrahlung
  - Nuclear interactions

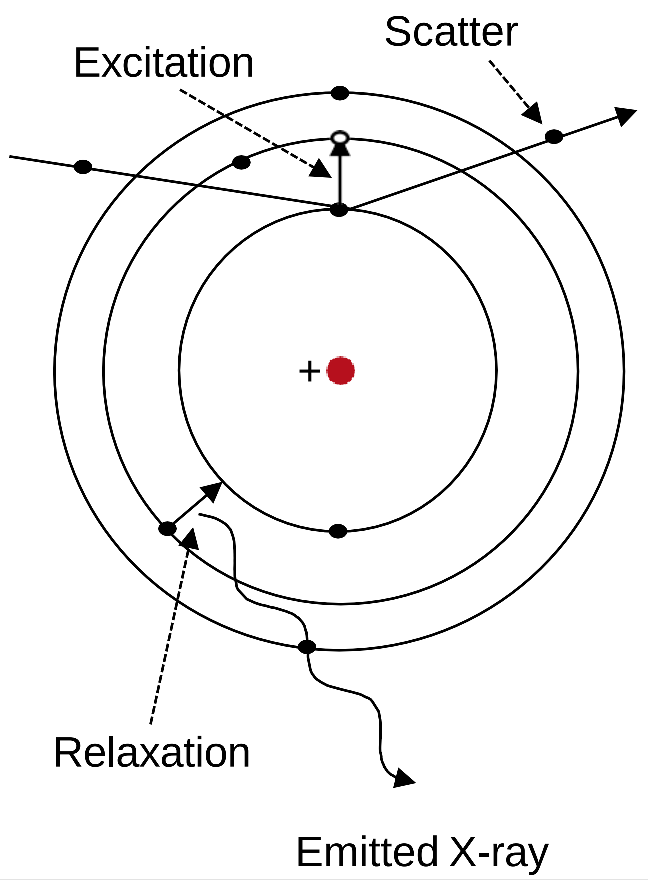
Electron-matter interactions

Interactions with shell electrons

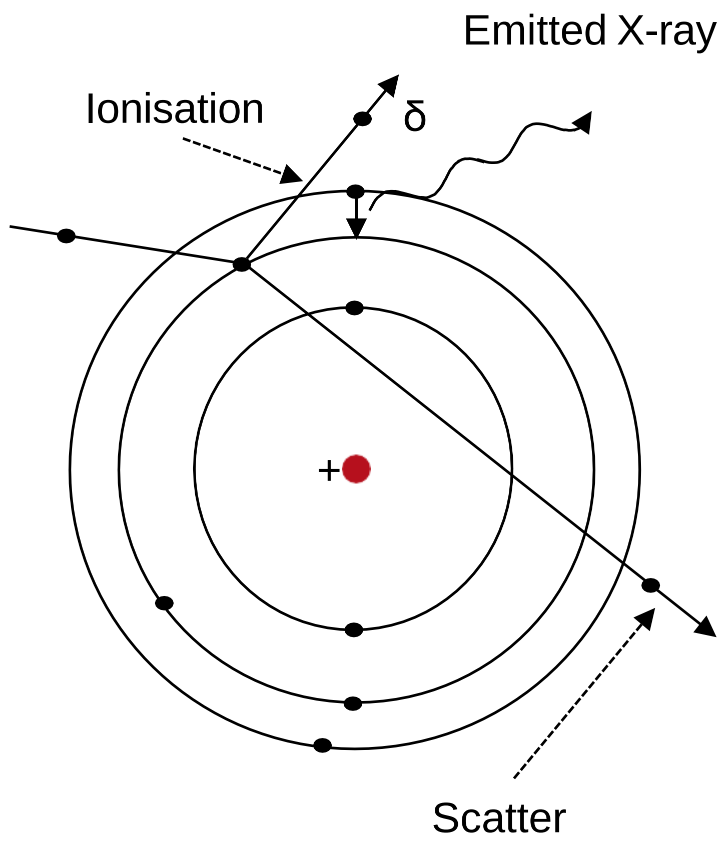
Elastic scattering



Excitation



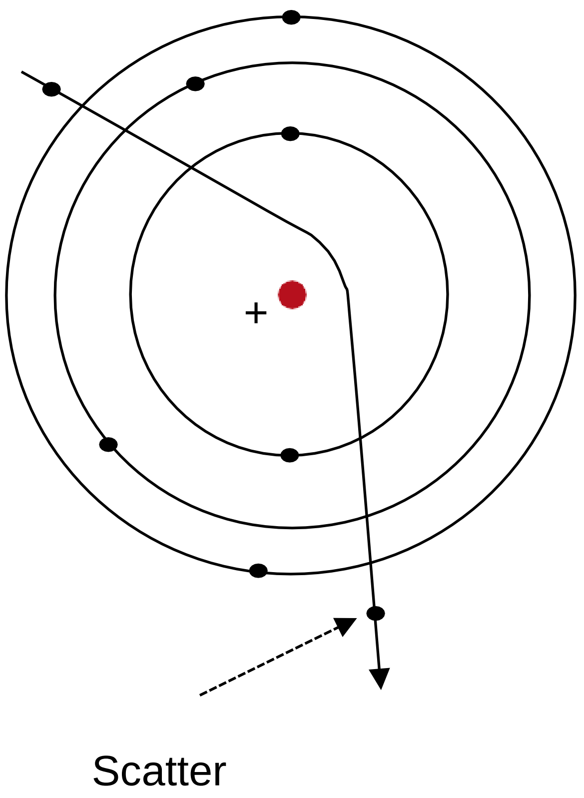
Direct Ionisation



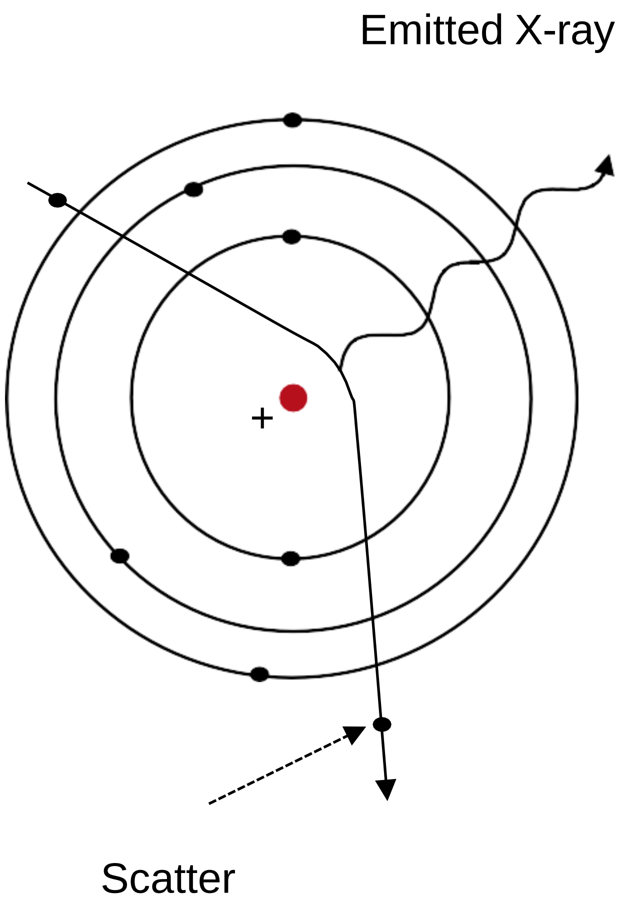
Electron-matter interactions

Interactions with nuclei

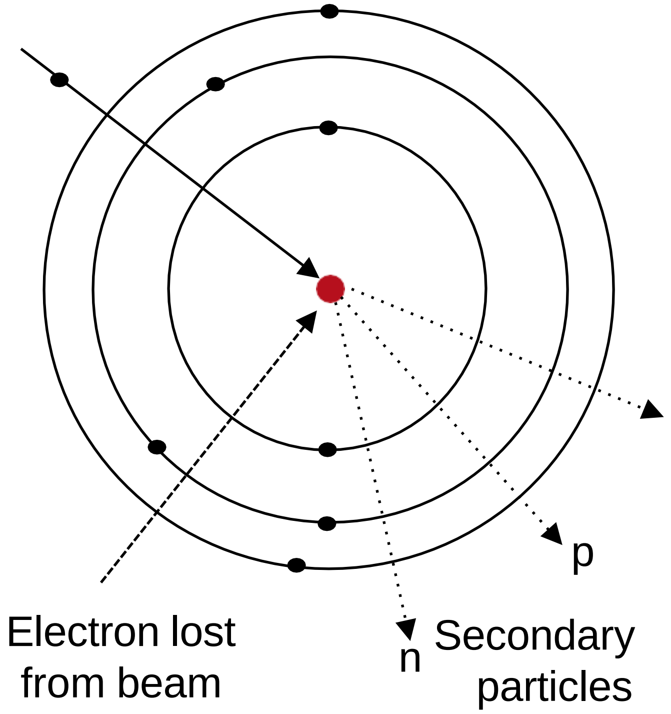
Elastic scattering



Bremstrahlung

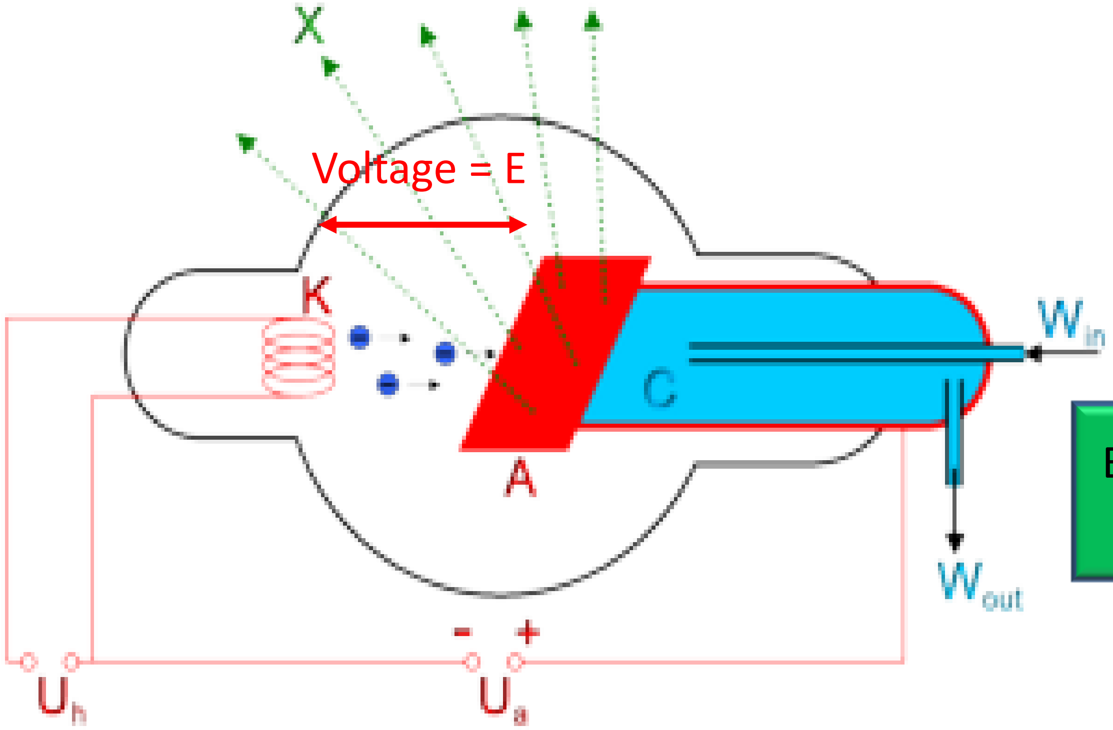


Nuclear interactions

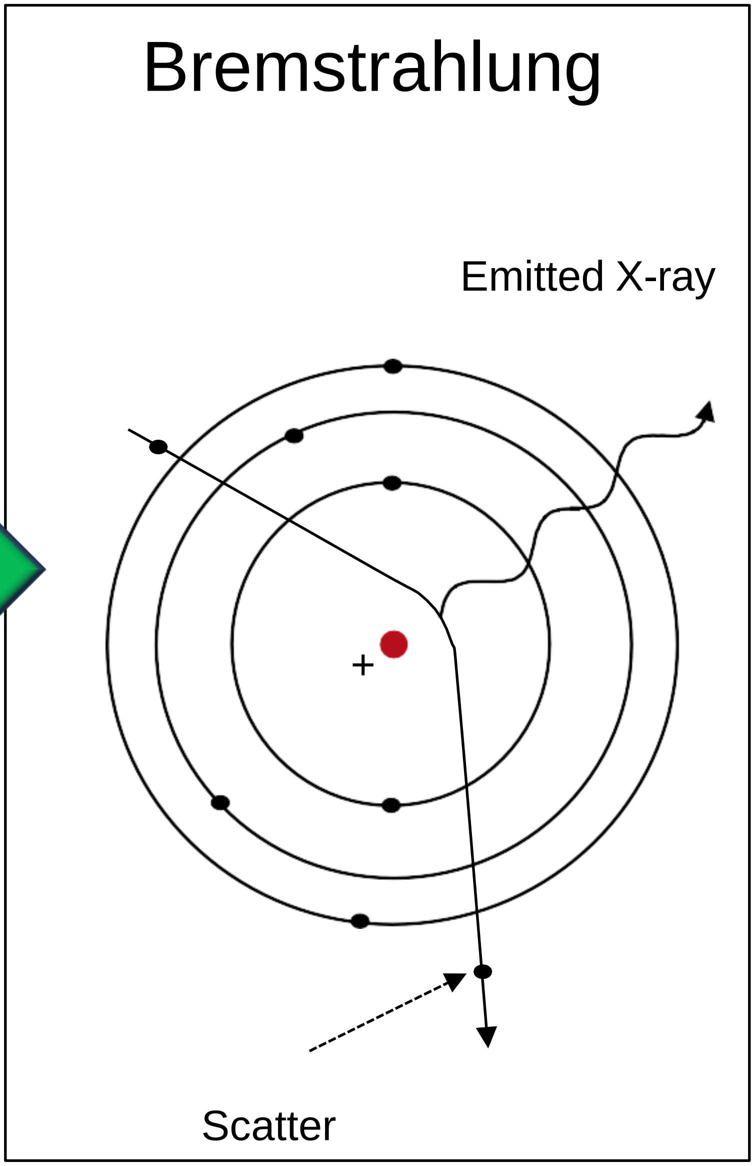


Electron-matter interactions

X-ray generation



Electrons accelerated onto metal target


Bremstrahlung

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

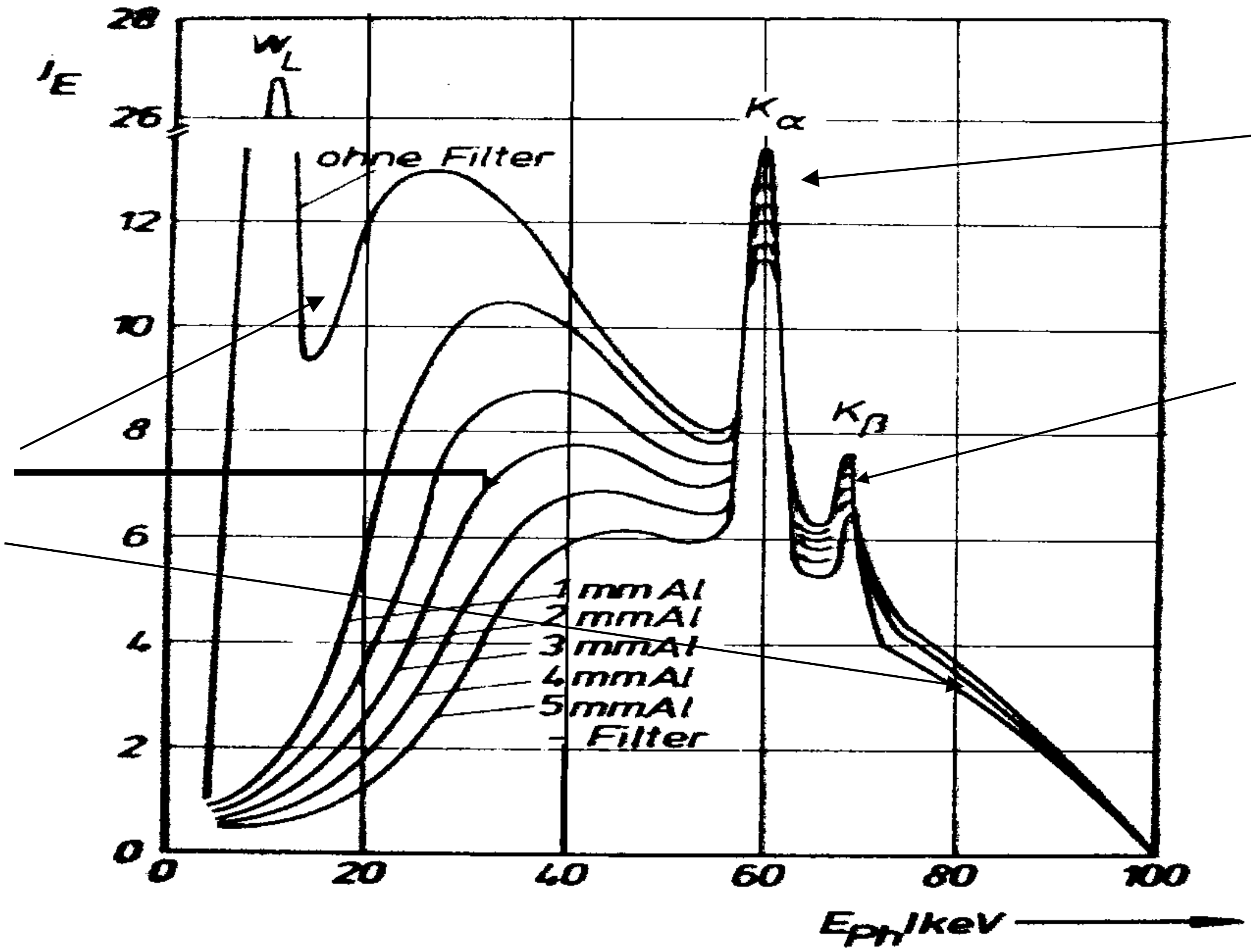
Electric fields *accelerate*

Magnetic fields *deflect*

The Lorenz force for *charged* particles

Electron-matter interactions

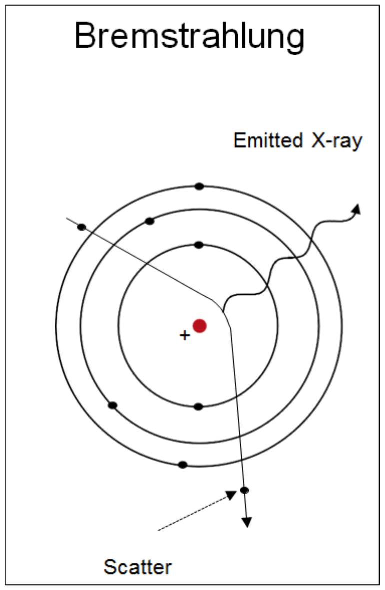
E.g. Spectrum from typical X-ray tube

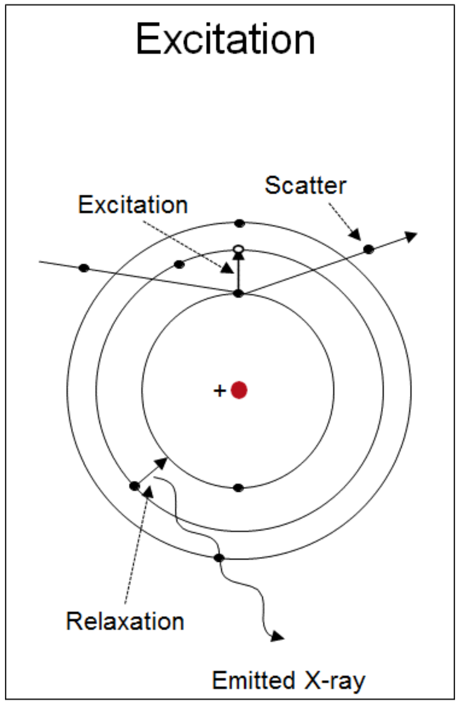


Characteristic energy for L-K shell transitions

Characteristic energy for M/N-K shell transitions

Bremstrahlung continuum





3. Interactions of radiation with matter

Photons

Photon-matter interactions

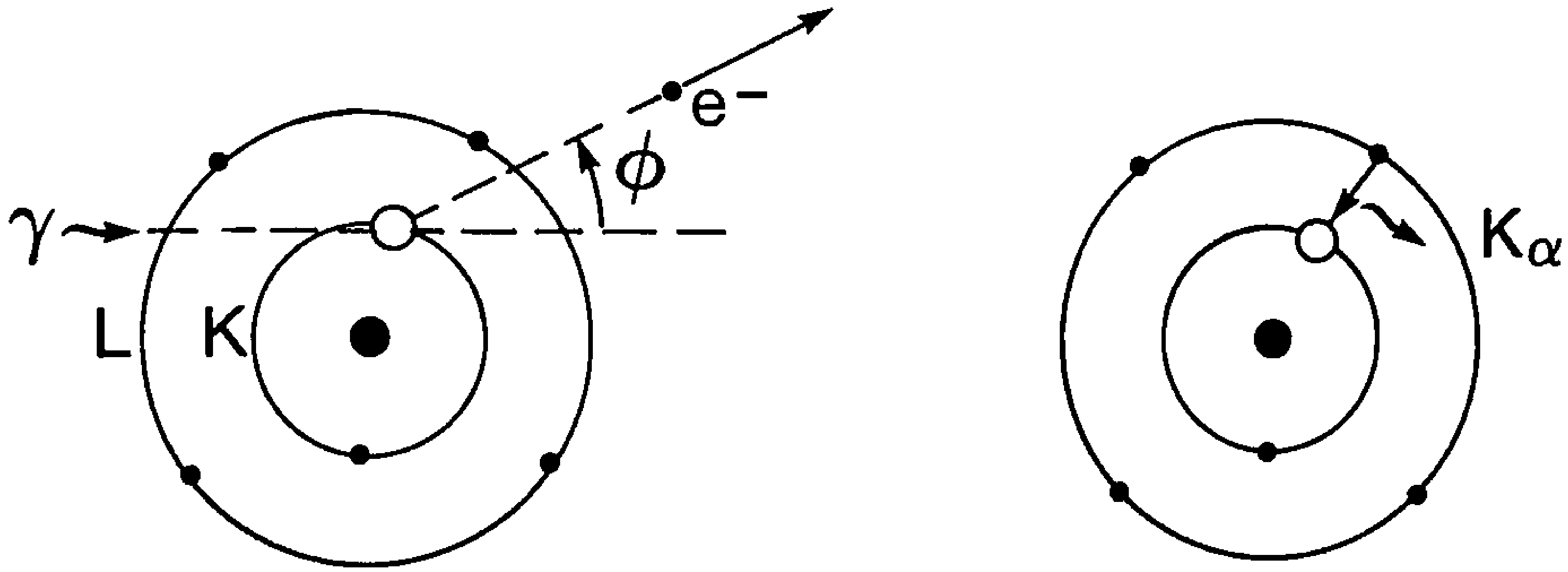
Principle interactions

- Elastic Scattering (Rayleigh~, Thomson~)

- Absorption by electrons (**photoelectric effect**)
- Inelastic scattering (**Compton scattering**)
- Absorption by the nucleus or its Coulomb-field (**pair production**)

Photon-matter interactions

The Photoelectric Effect τ



Photon-matter interactions

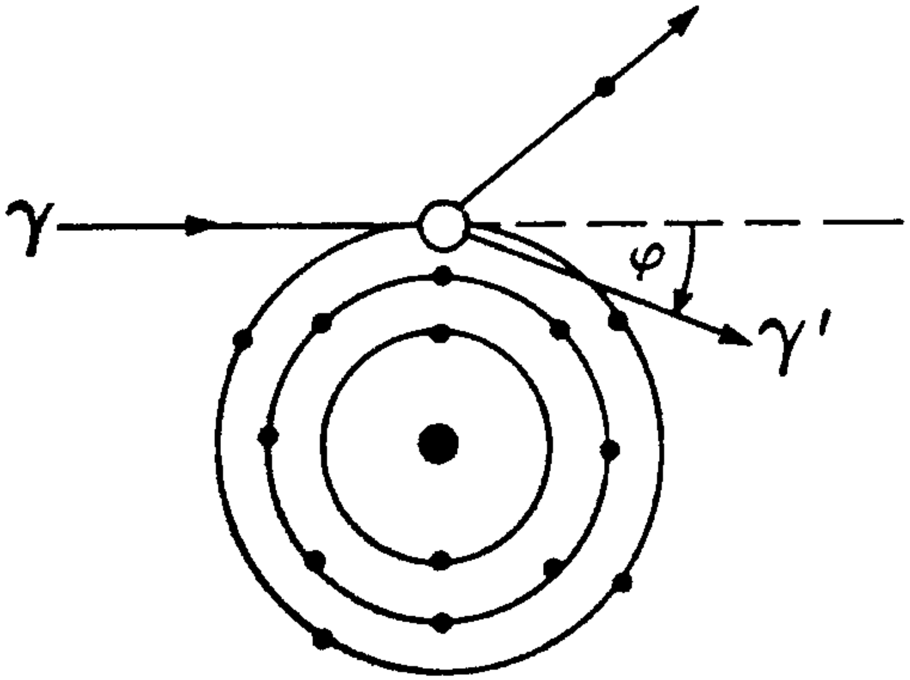
The Photoelectric Effect τ

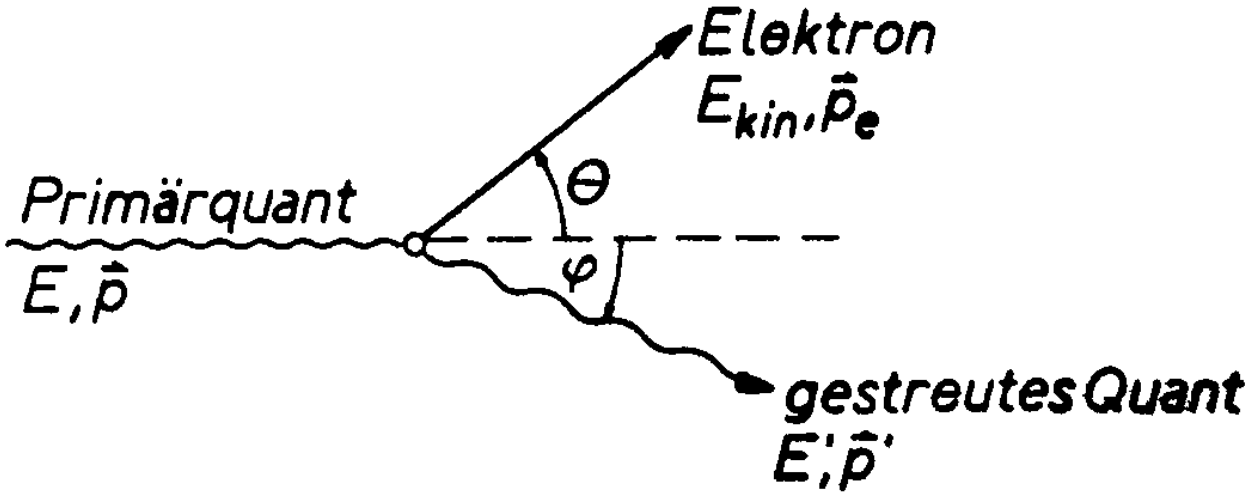
$$h \cdot \nu = E_{kin}^{e-} + E_{bind}^{e-} \qquad \tau \propto \frac{Z^3}{E^3} \cdot \rho$$

- Removal of an interior shell electron
- Steep decrease in probability with increasing energy
- Strong dependency on absorber‘s Z
- Linear density dependency much less important than Z relation.

Photon-matter interactions

The Compton effect σ





Photon-matter interactions

The Compton effect σ

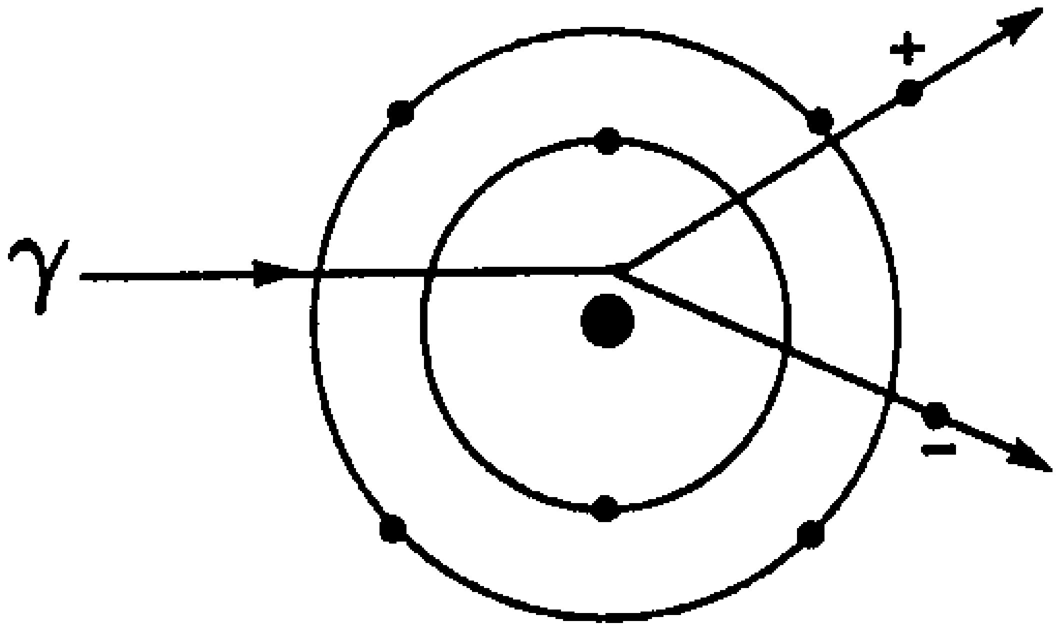
$$h \cdot \nu = E_{kin}^{e-} + E_{bind}^{e-} + h \cdot \nu'$$

$$\sigma \propto \frac{Z}{A} \cdot \enclose{circle}{\rho}$$

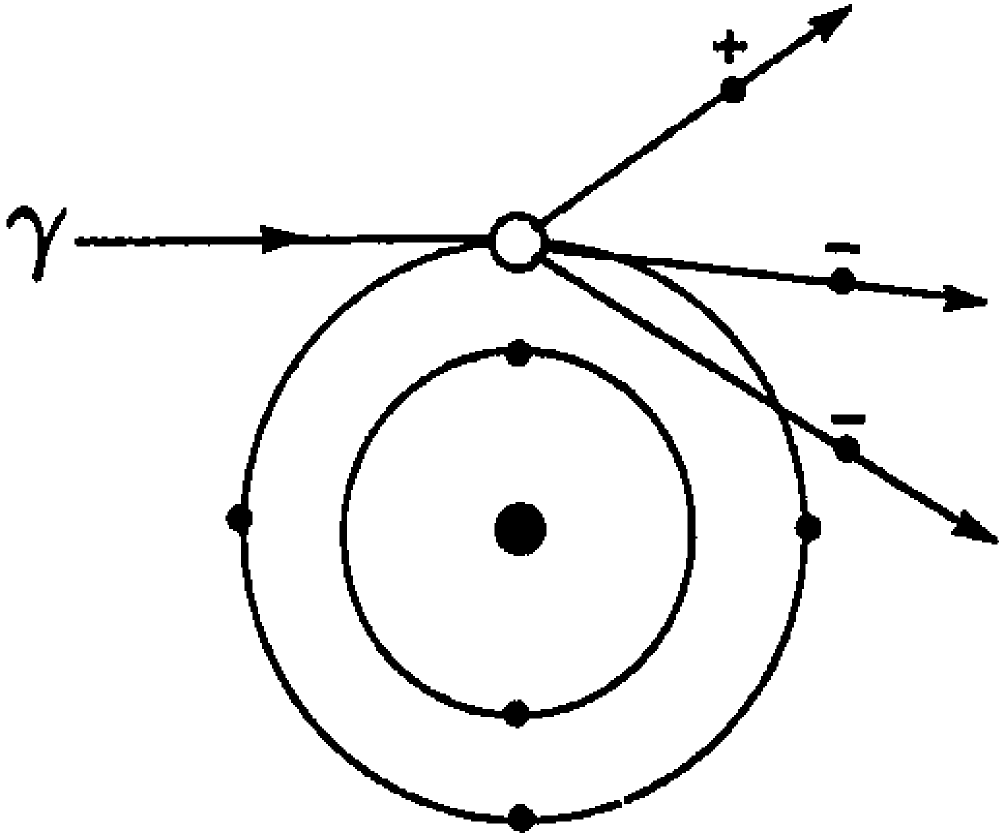
- Removal of a loosly bound outer shell electron (binding energy small)
- *Z/A* approximately constant (0,4 – 0,5)
- Linearly related to density

Photon-matter interactions

Pair production κ



$E_\gamma > 1022$ keV



$E_\gamma > 2044$ keV

Photon-matter interactions

Pair production κ

$$h \cdot \nu = E_{kin}^{e-} + E_{kin}^{e+} + 2E_{0}^{e+/-}$$

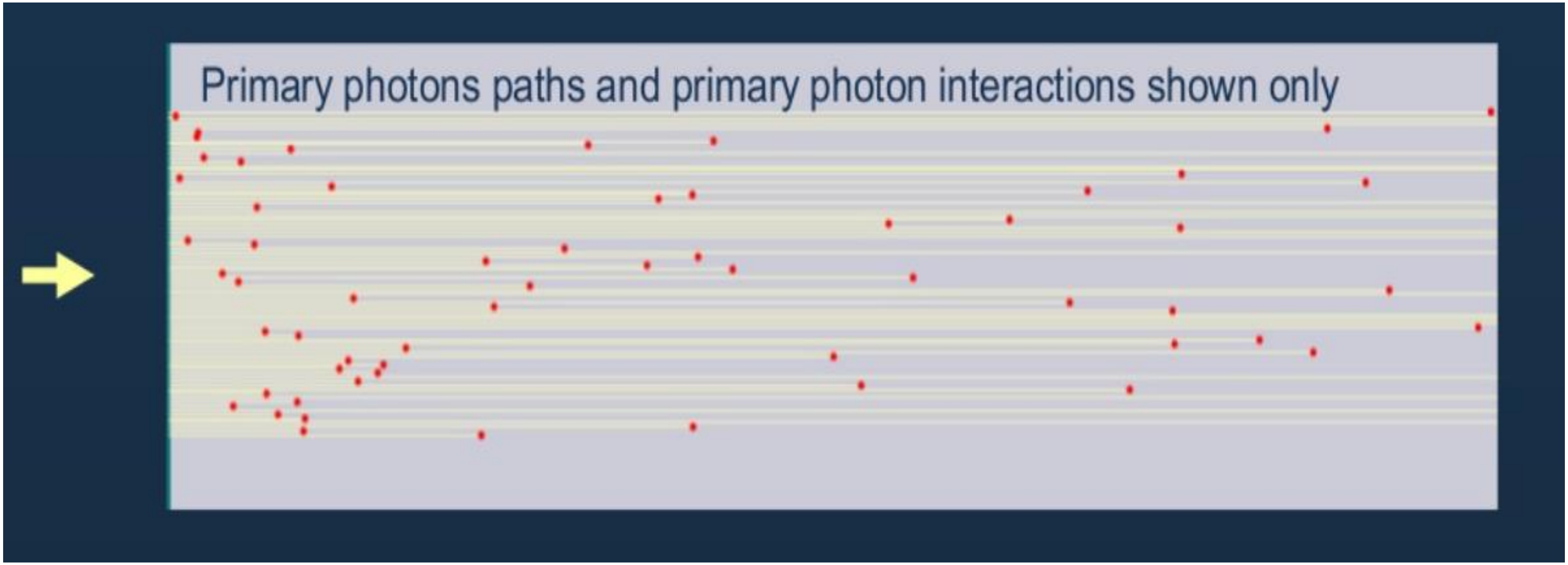
$$\kappa \propto Z \cdot \rho \cdot \lg(h \cdot \nu)$$

- Rest energy (mass) of an electron/positron = 511 keV
- Low energy border at: $2 * m_e * c^2 = 1022$ keV
- Overwhelms Compton scattering ($\sigma/\rho = \kappa/\rho$) at 25 MeV in water

Photon-matter interactions

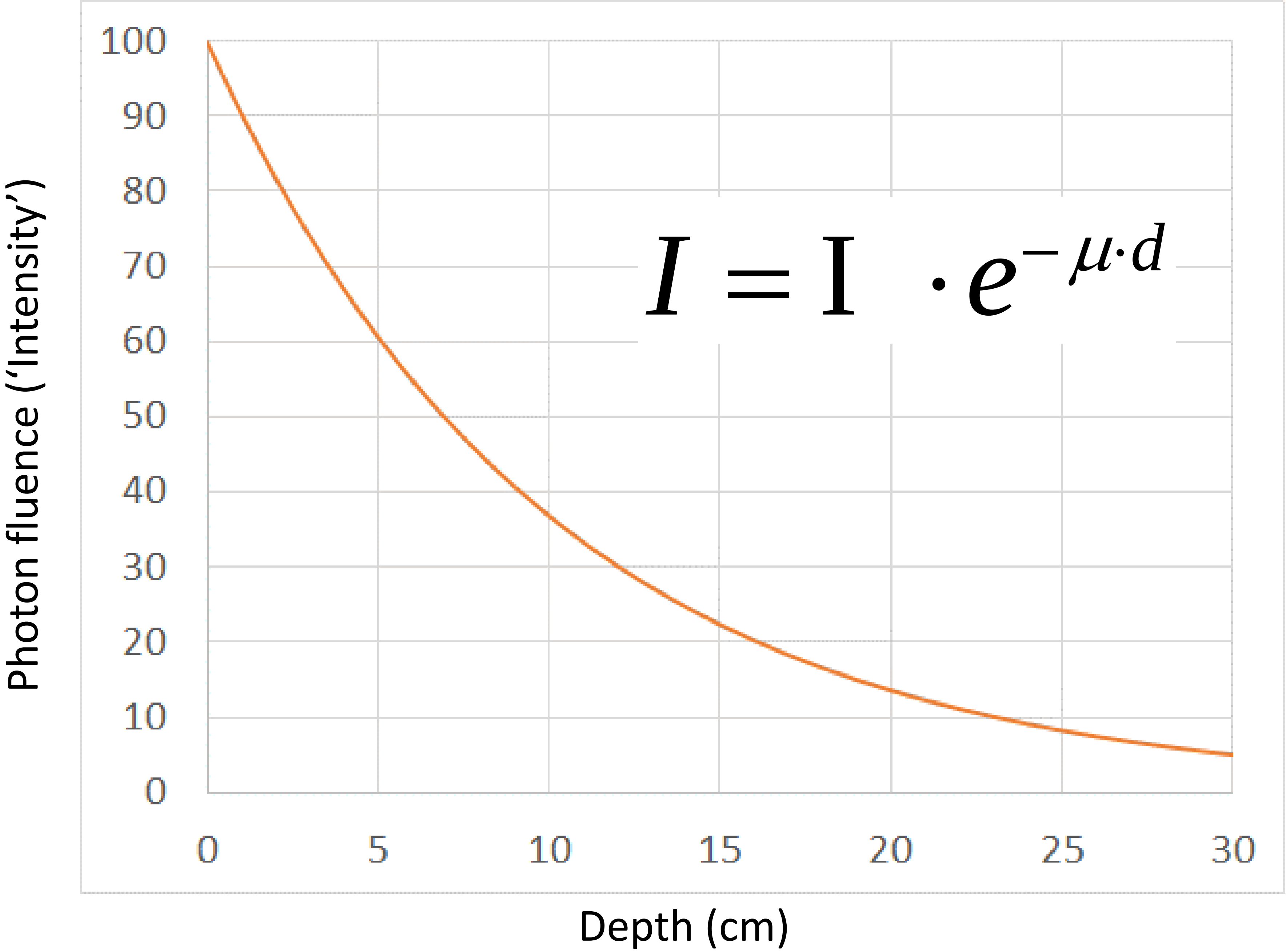
Photon attenuation

Loss of photons (scattered/absorbed) as function of penetration of beam



Photon-matter interactions

Photon attenuation



$$I = \mathrm{I} \quad \cdot e^{-\mu \cdot d}$$

Photon-matter interactions

Attenuation coefficient

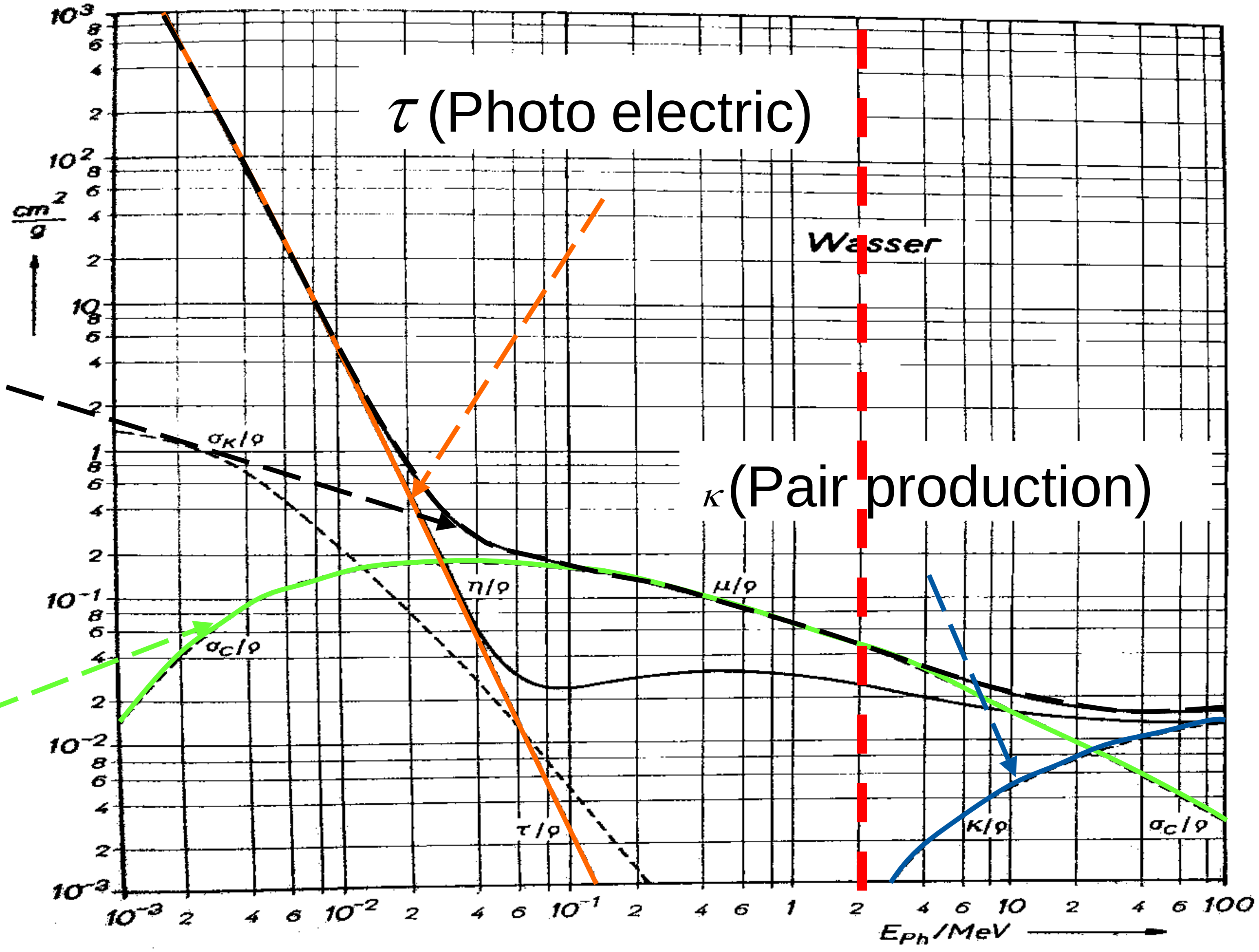
All attenuation coefficients are density-dependant => Formalism of mass attenuation coefficient (attenuation per unit mass)

$$\mu_m = \mu / \rho$$

Linear attenuation coefficient μ	1 / cm
Mass attenuation coefficient μ_m	cm^2 / g

Photon-matter interactions

Attenuation coefficient



τ (Photo electric)

μ_m (Total)

κ (Pair production)

σ (Compton scattering)

Mean energy of 6MV photons

3. Interactions of radiation with matter

Protons

Electrons and protons compared

$$m_p = 1800 \times m_e$$

An electron

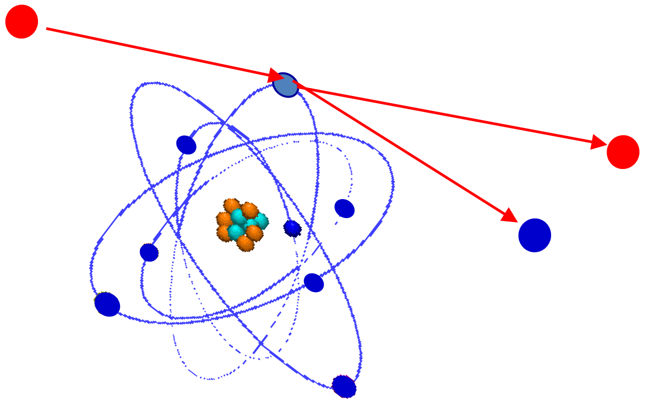
My bike ~ 6.5kg

A proton

A M113 Tank ~ 12500kg

Principle interactions of protons.

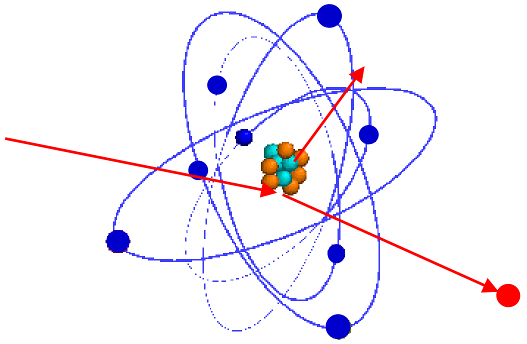
Direct ionisation



$$\frac{-dE}{dX} \propto \frac{1}{\beta c^2}$$

Predominate effect for energy loss and deposition

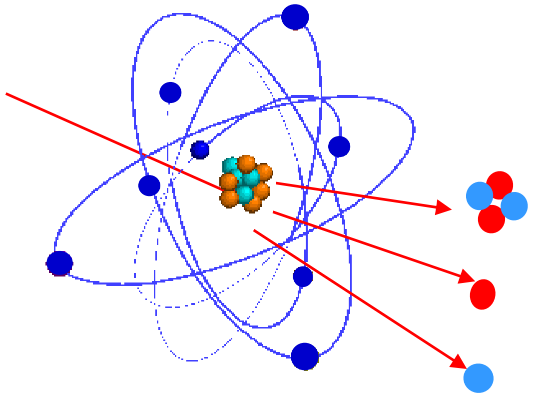
Nuclear (Coulomb) scattering



$$\theta_0 \sim \frac{\sqrt{\rho x}}{v^2} \frac{Z}{\sqrt{A}}$$

Predominate effect for lateral scatter

Inelastic nuclear interactions

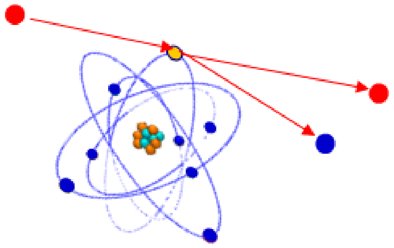


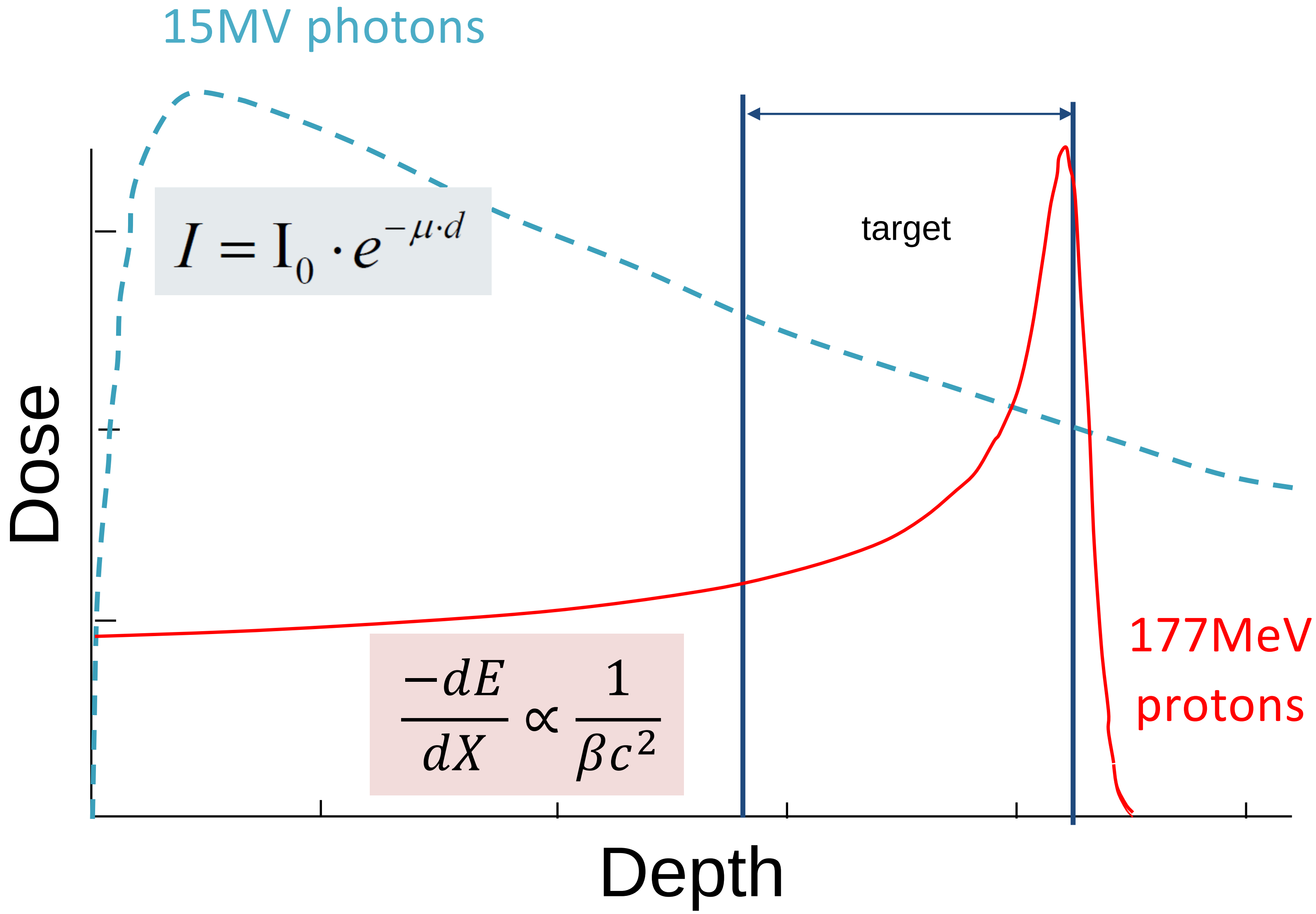
$$\emptyset_d \sim \emptyset_0 - 0.01 d(cm) \emptyset_0$$

Predominate effect for loss of proton fluence (absorption)

Interactions of protons

Energy loss



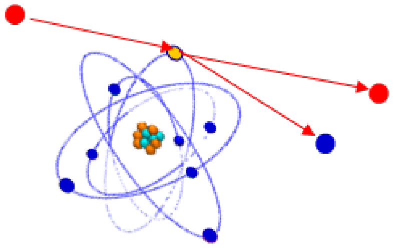


$$I = I_0 \cdot e^{-\mu \cdot d}$$

$$\frac{-dE}{dX} \propto \frac{1}{\beta c^2}$$

Interactions of protons

Energy loss

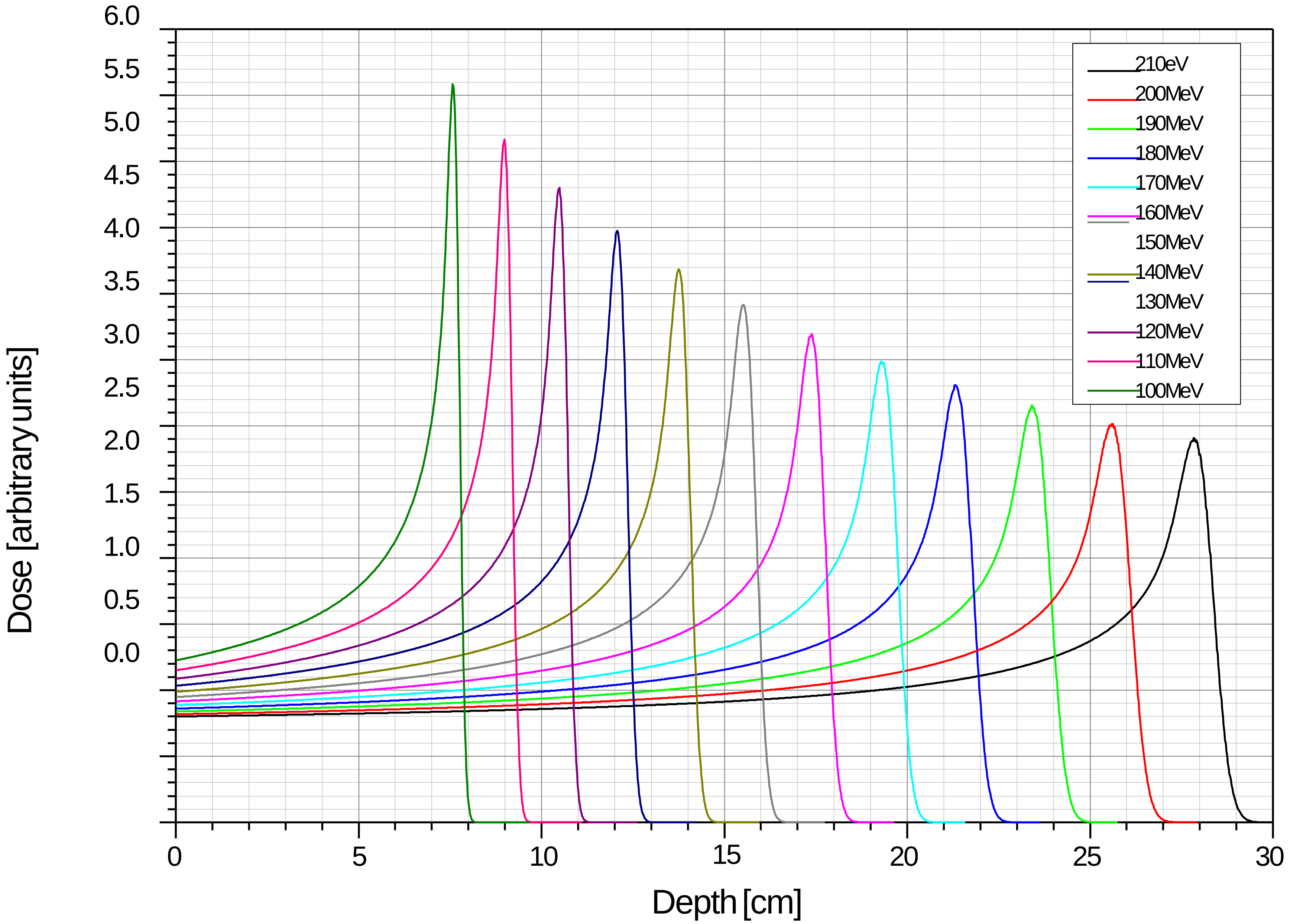


Range and shape of the depth dose curve (Bragg peak) dependent on incident energy

Ranges in water

210MeV – 28cm

100MeV – 7.5cm



Overview of presentation

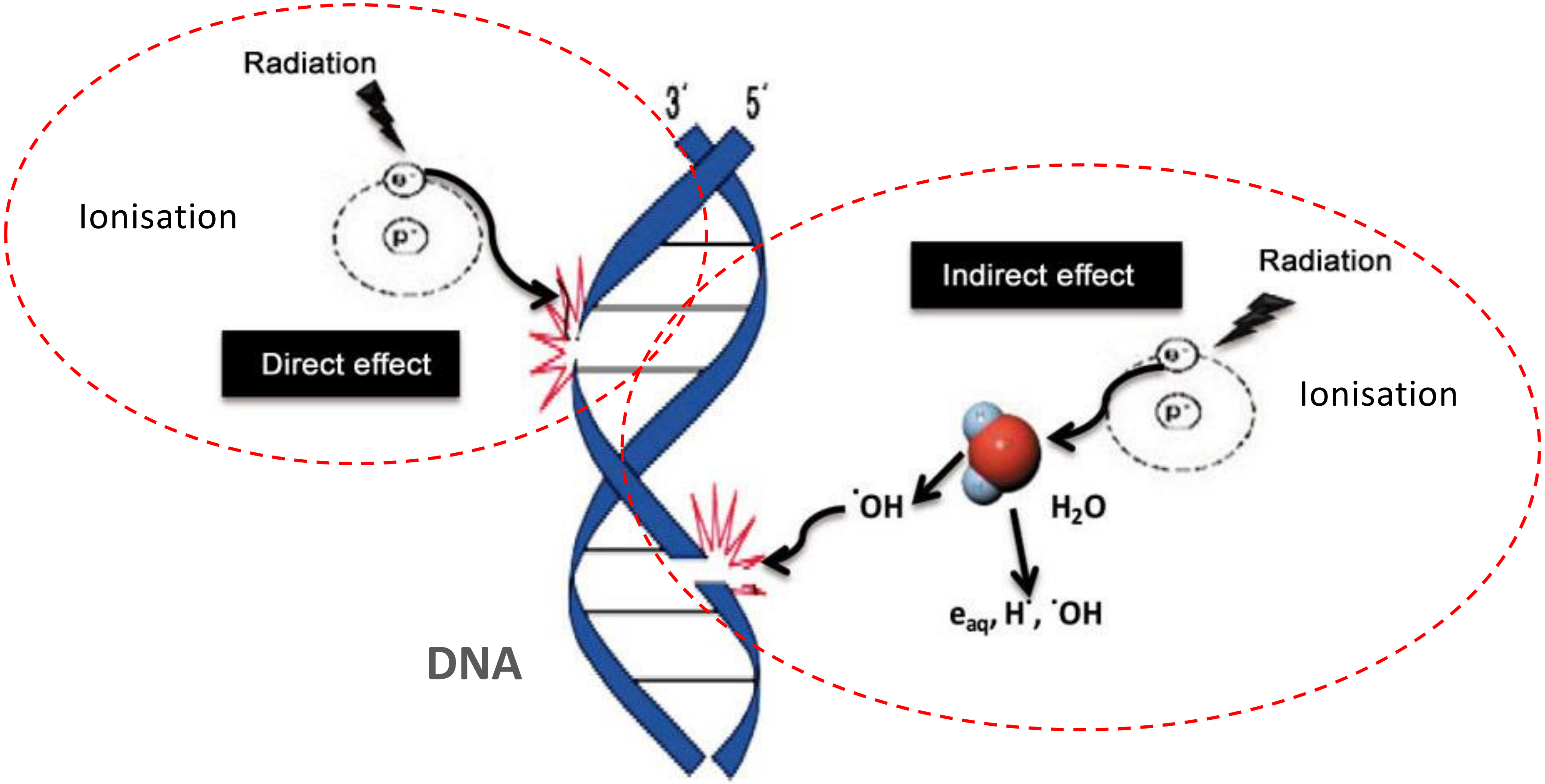
1. A brief history of radiotherapy

2. Fundamentals of radioactivity

3. Interactions of radiation with matter

4. The physics of radiotherapy

Ionisation and radiation damage

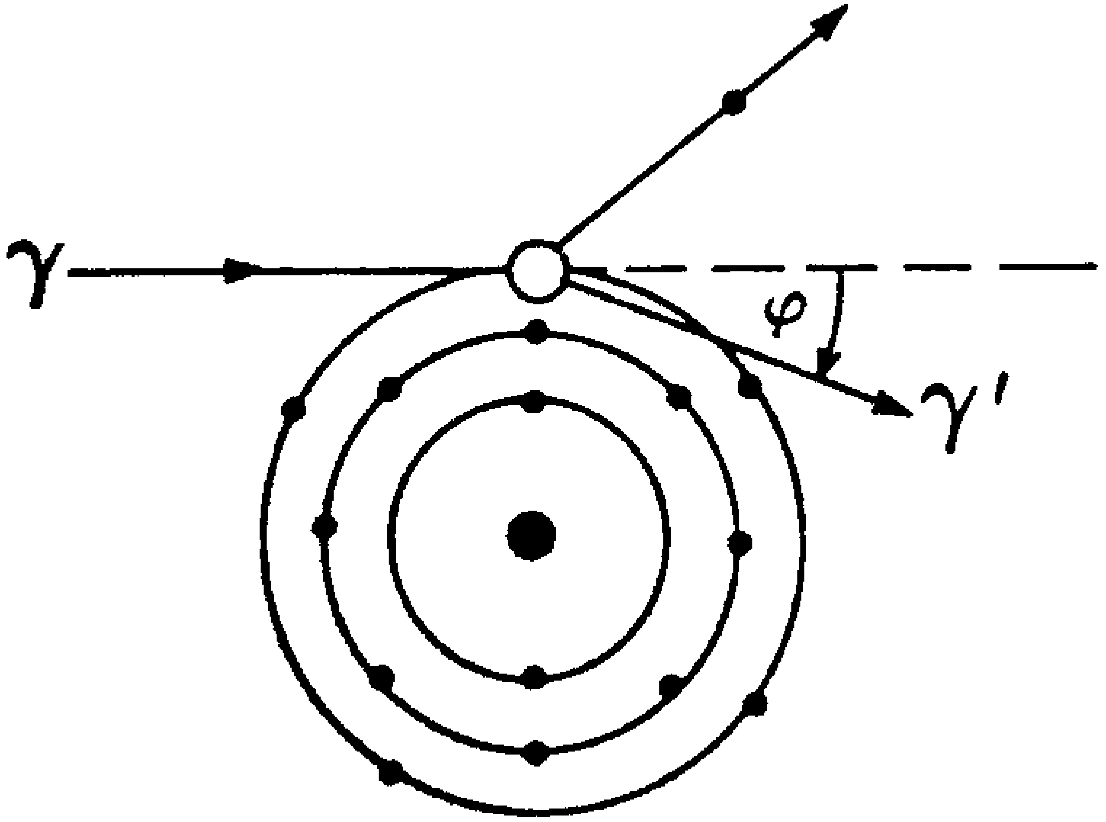


Radiation induced *ionisation* damages DNA either directly (rare) or indirectly through production of oxygen free-radicals (more common)

It's all to do with ionisation…

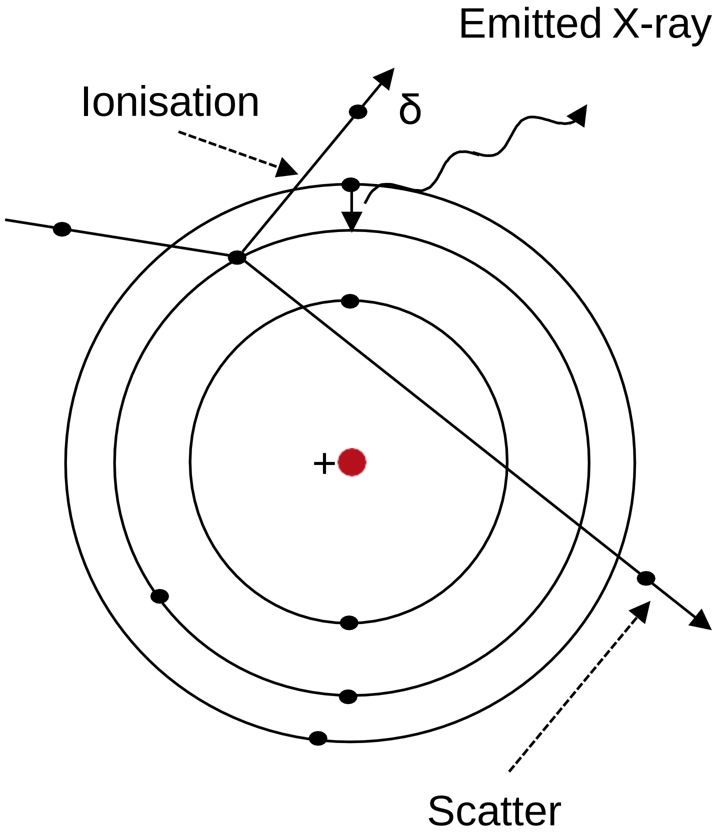
For photons…

Compton effect

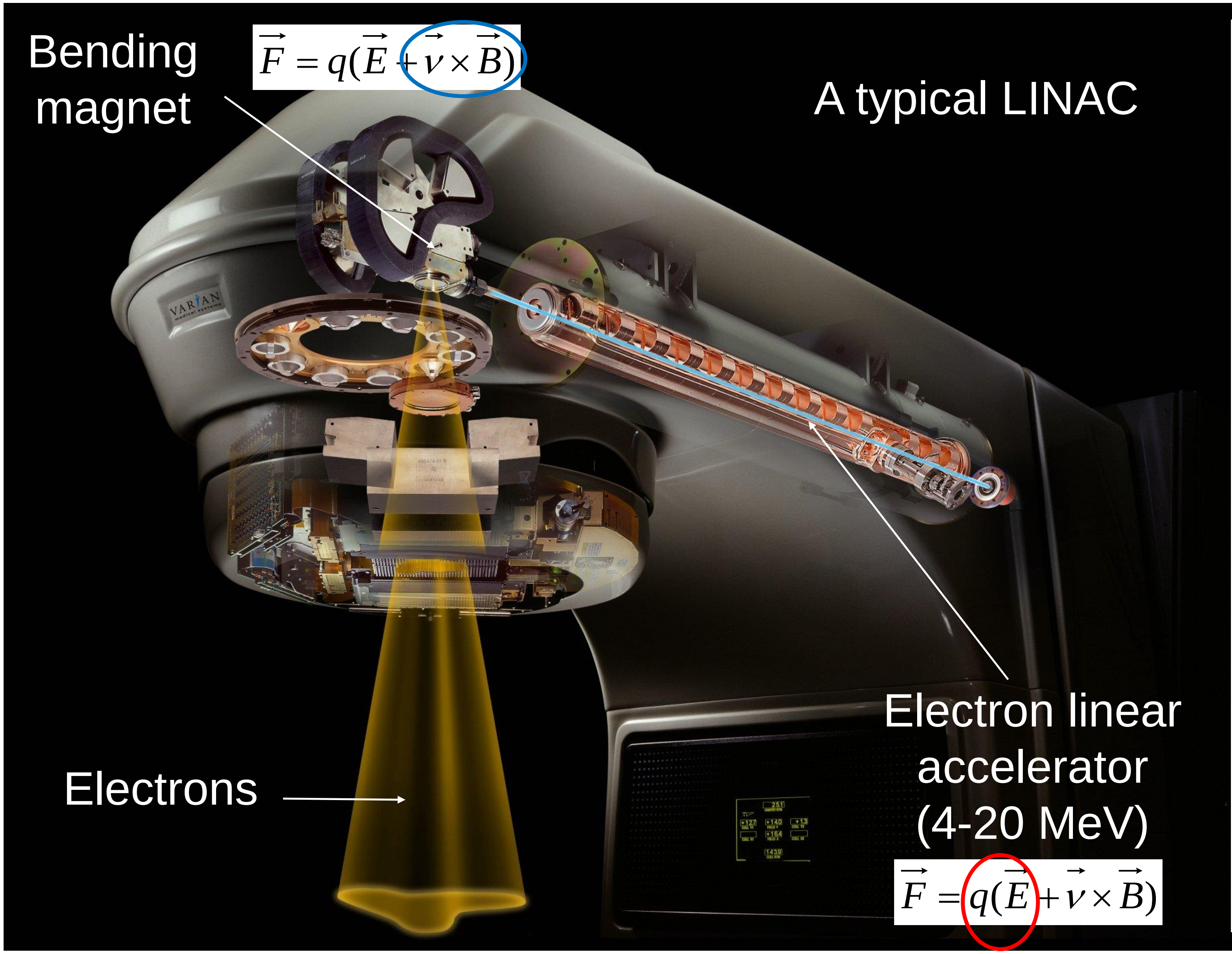


…and electrons/protons

Direct ionisation



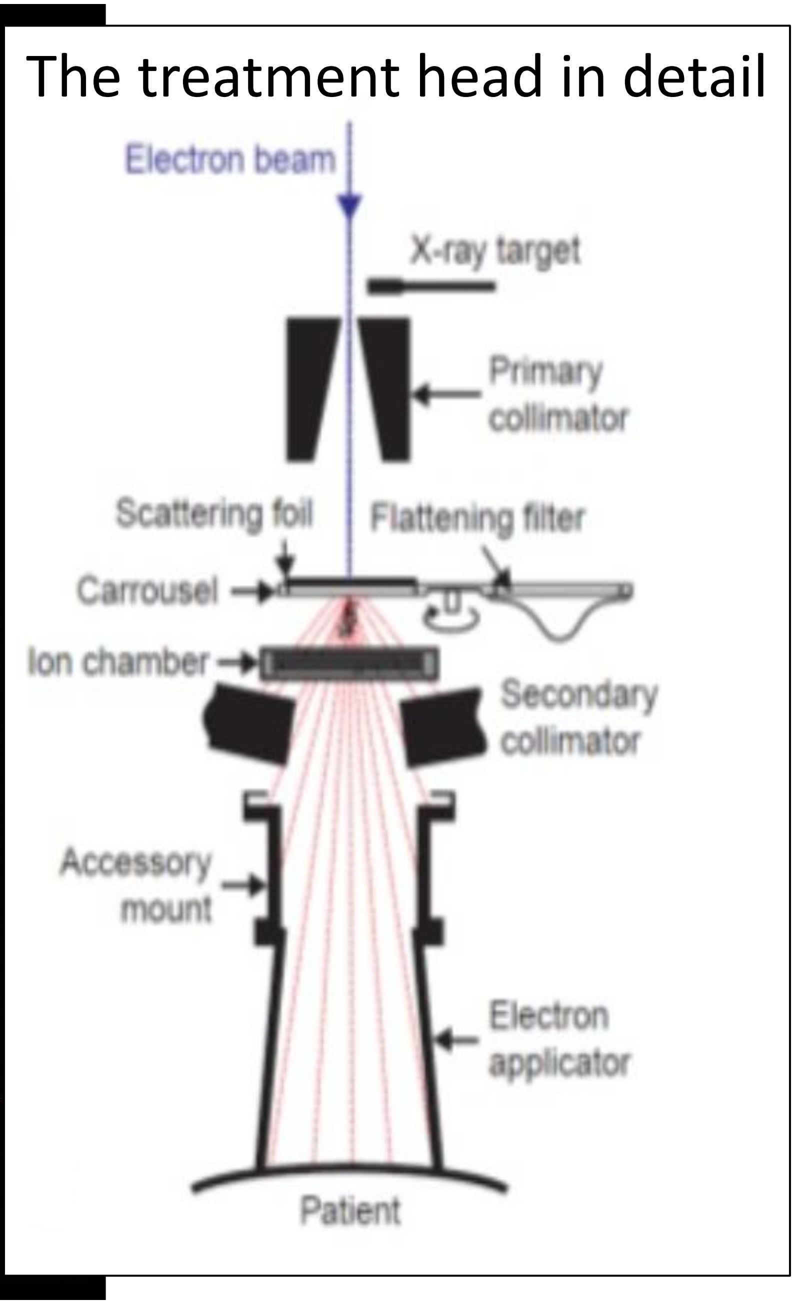
Generating electrons for radiotherapy



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

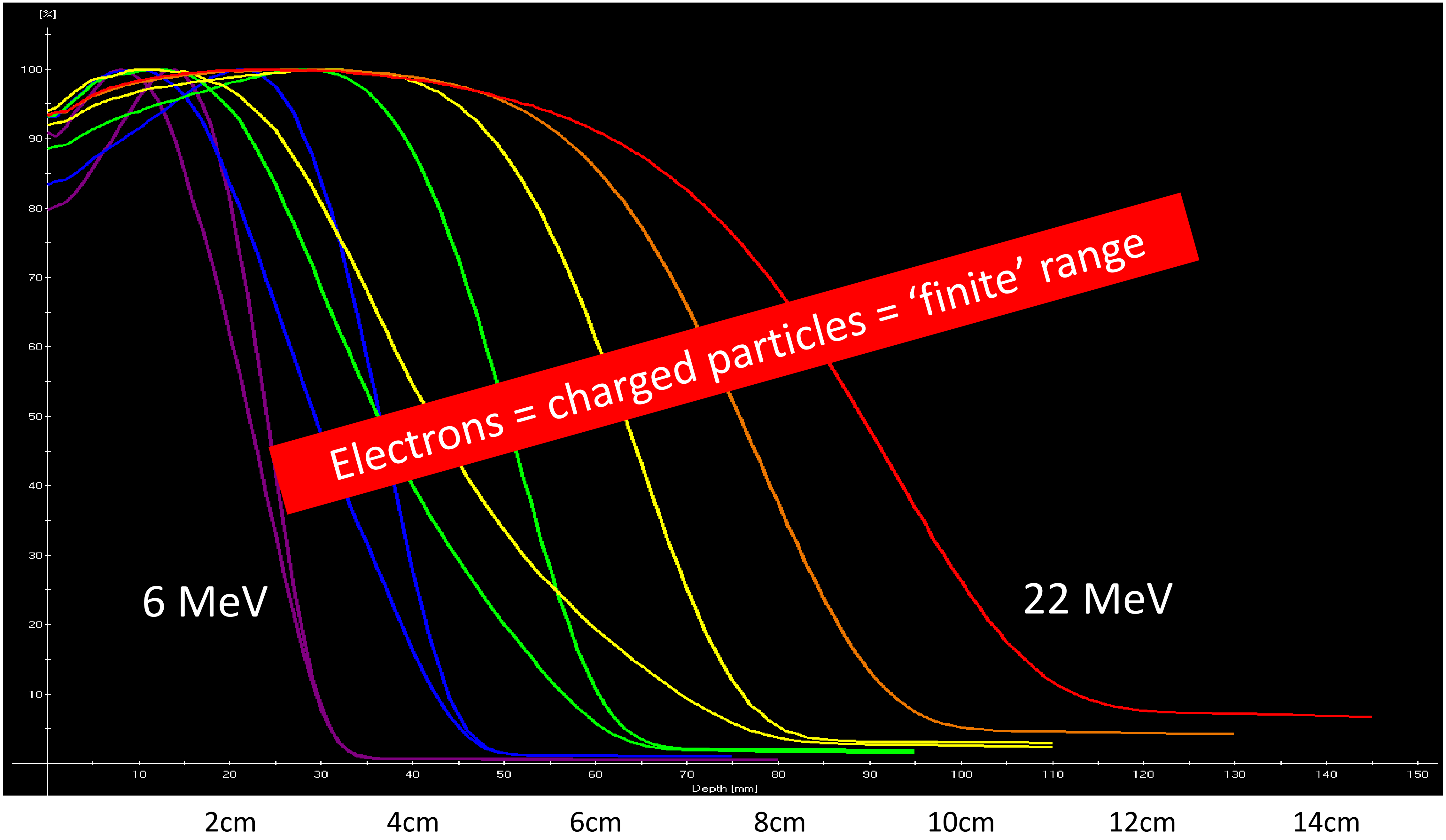
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

The treatment head in detail



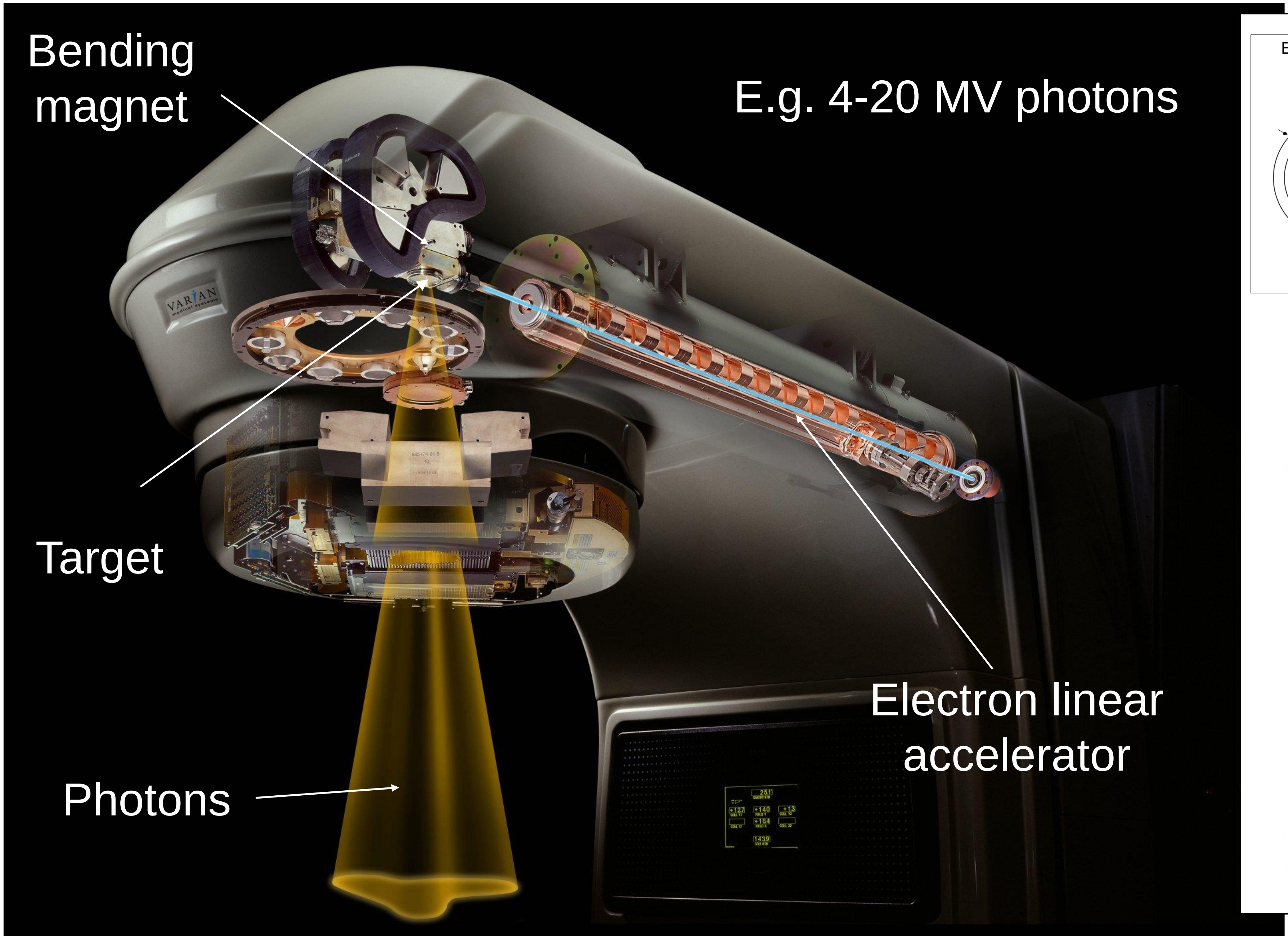
https://www.slideshare.net/Julfikar2/discussion-about-machines-of-radiotherapy-linac-cobalt-60

Electrons in radiotherapy

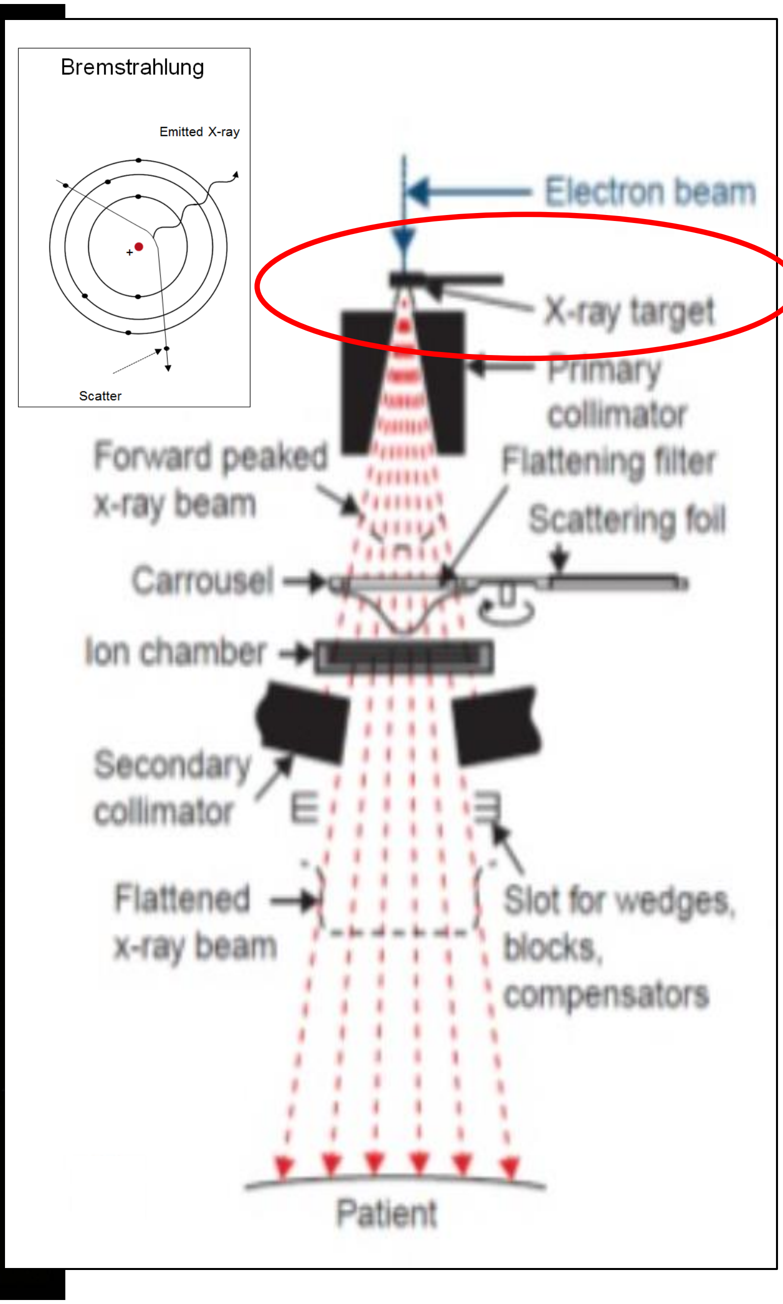


Electrons = charged particles = ‘finite’ range

Generating photons for radiotherapy

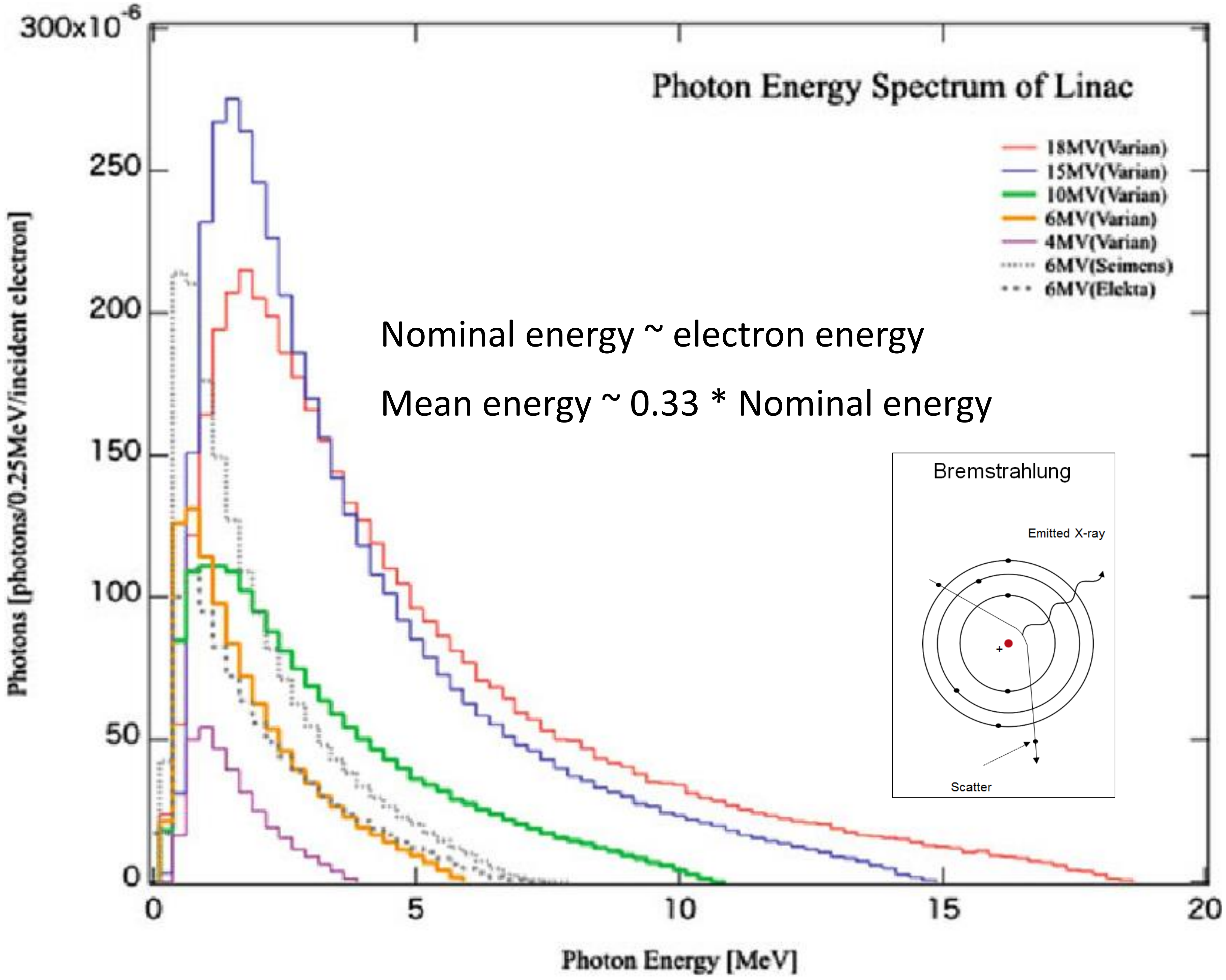


E.g. 4-20 MV photons



https://www.slideshare.net/Julfikar2/discussion-about-machines-of-radiotherapy-linac-cobalt-60

Typical photon spectra from Linacs

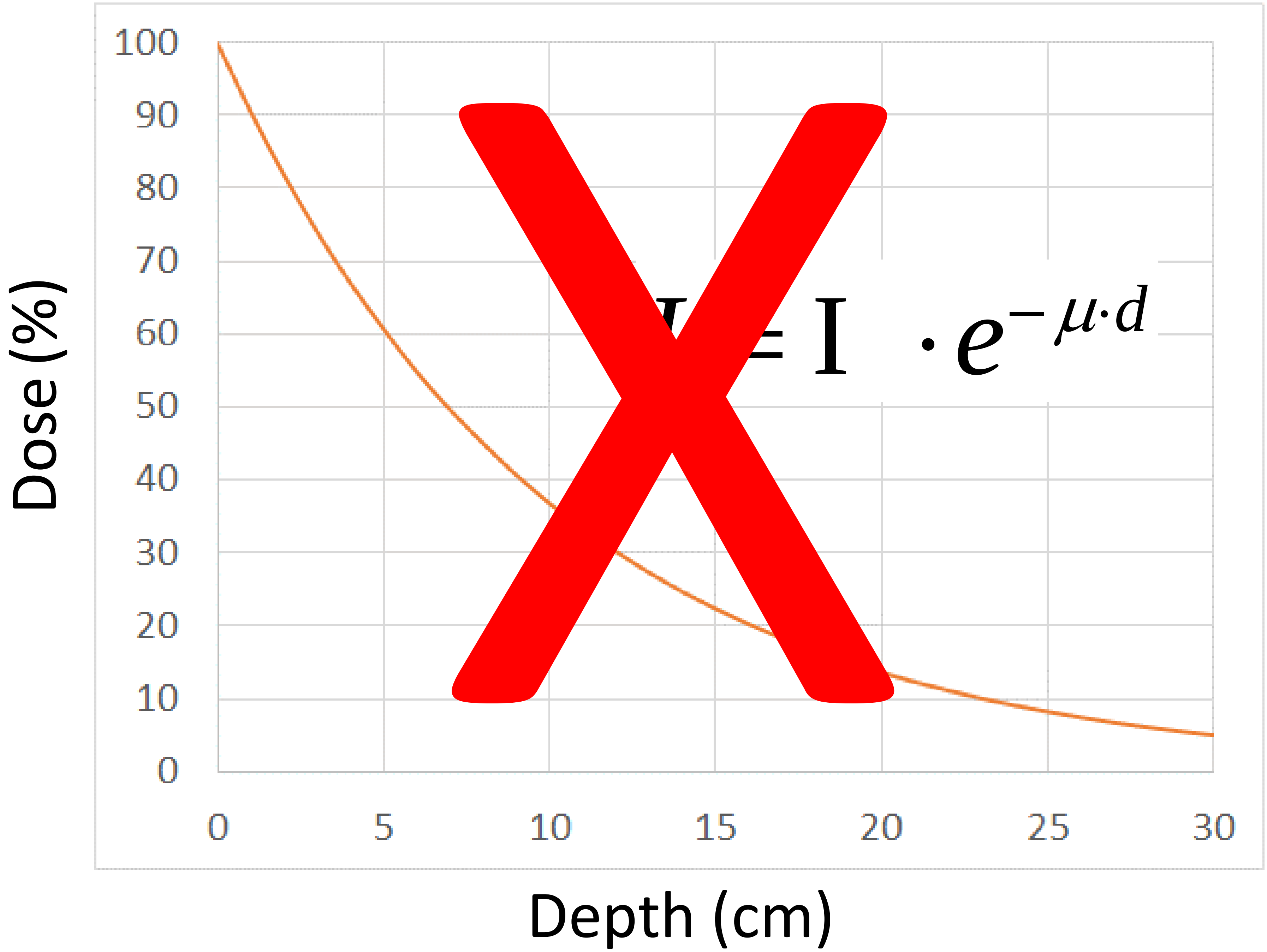


Nominal energy ~ electron energy

Mean energy ~ 0.33 * Nominal energy

https://www.researchgate.net/figure/The-X-ray-energy-spectra-of-Linac-2_fig13_299974488

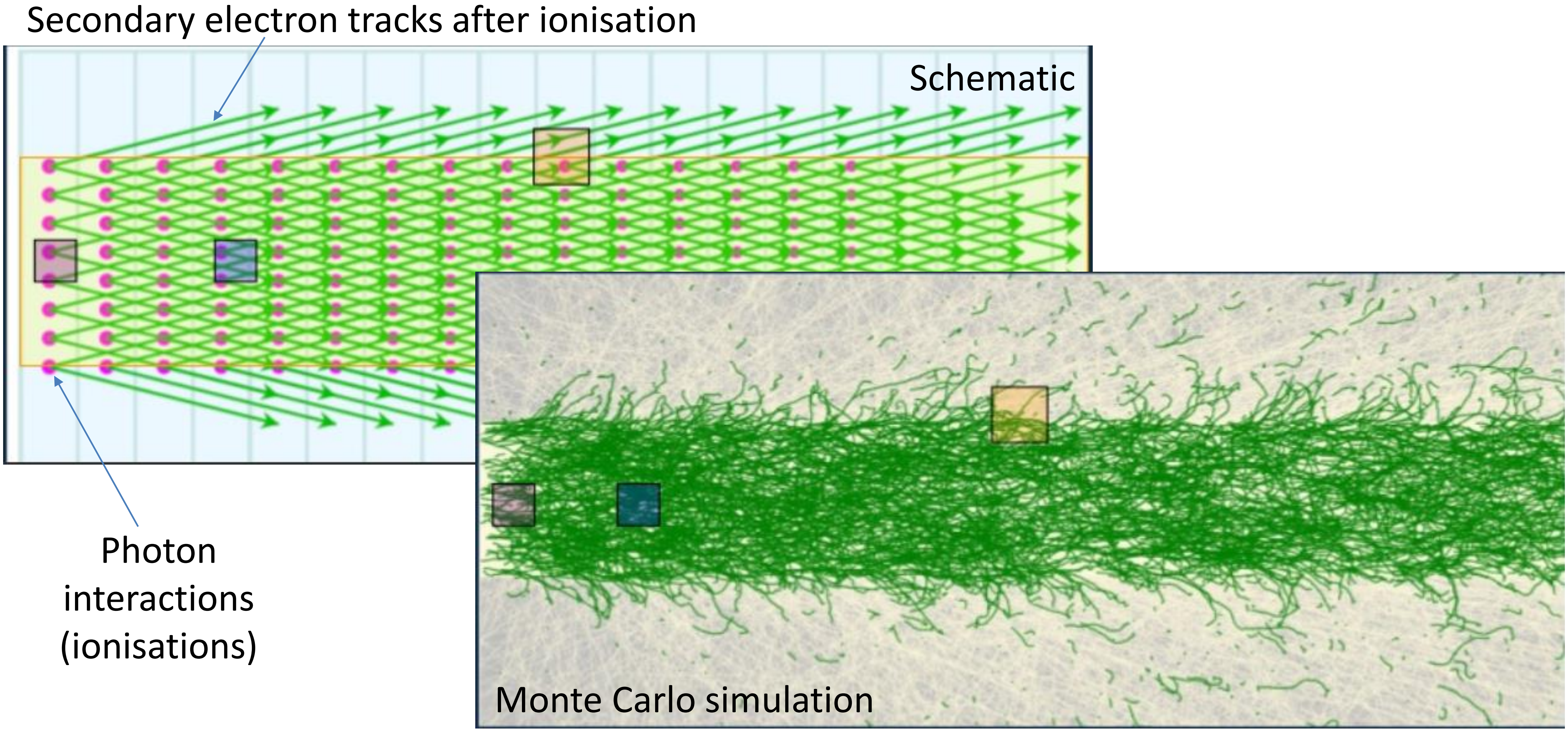
The photon depth-dose curve



$$I = I \cdot e^{-\mu \cdot d}$$

The photon depth-dose curve

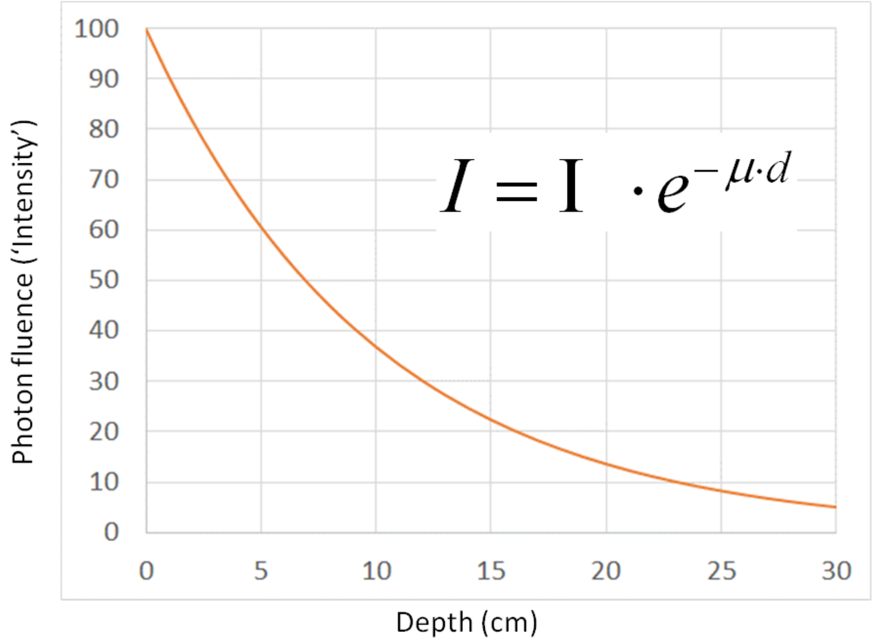
Energy is deposited by secondary electrons, *not* by photons (hence considered *indirectly* ionizing…)



https://www.slideshare.net/snaqvi69/visualizing-radiation-physics

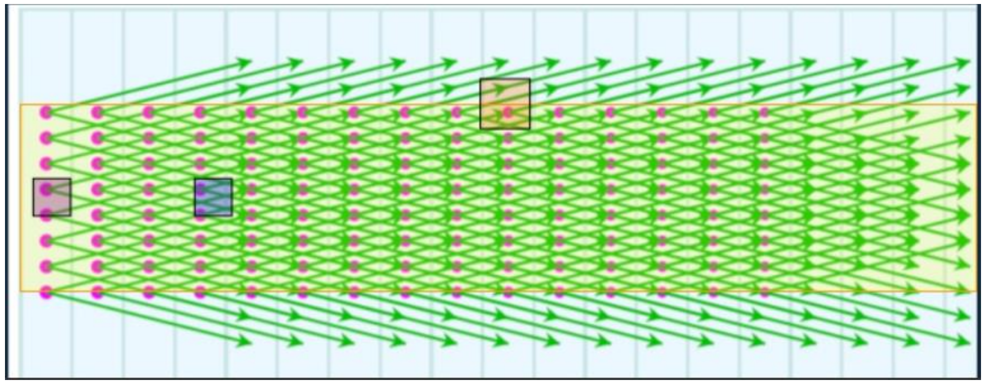
The photon depth-dose curve

Energy is deposited by secondary electrons, *not* by photons



$$I = \mathrm{I} \cdot e^{-\mu \cdot d}$$

+



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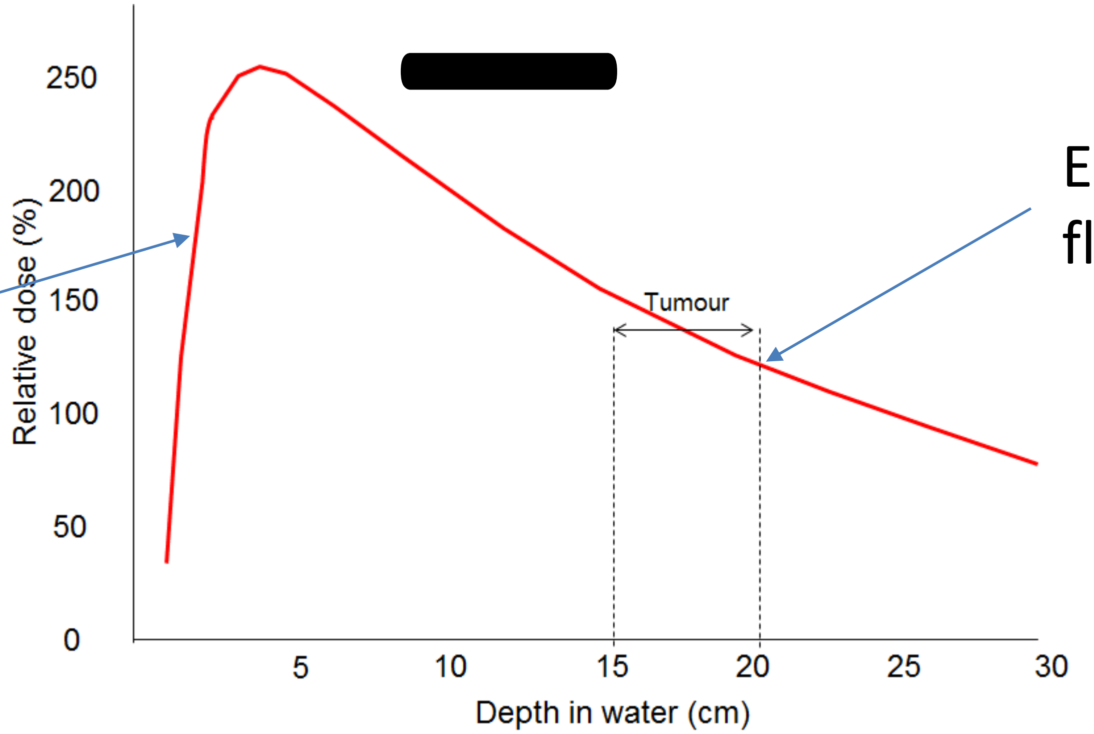
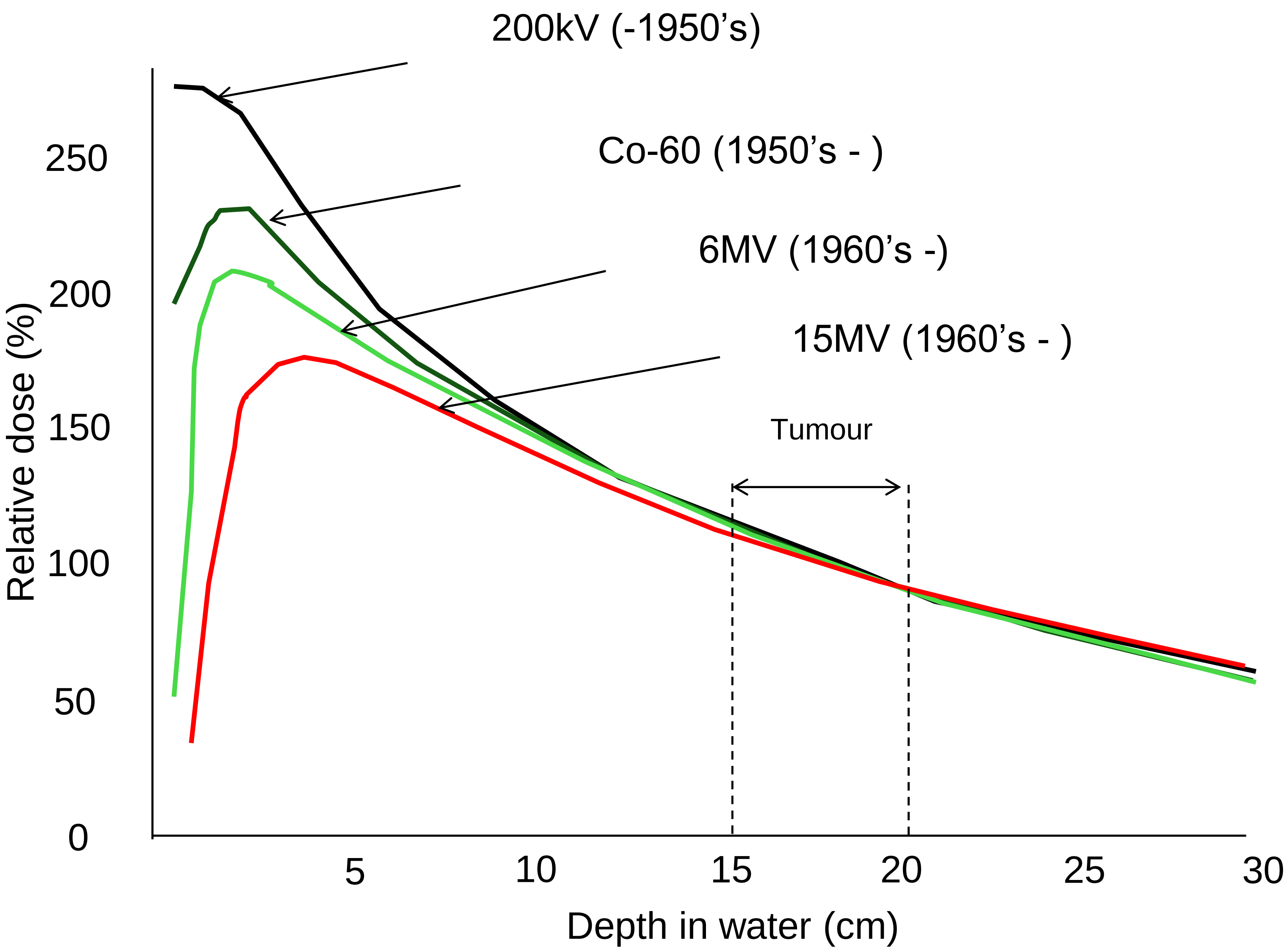
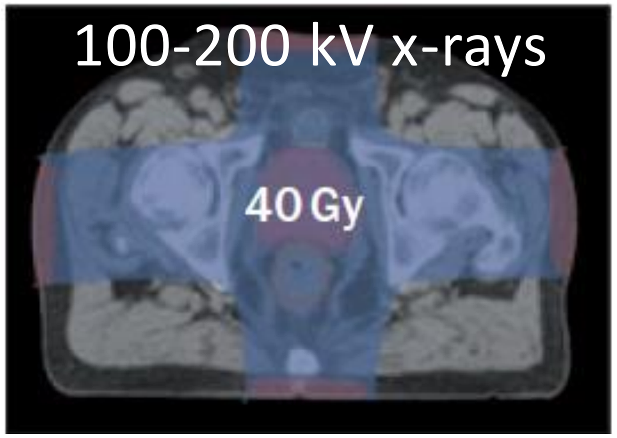


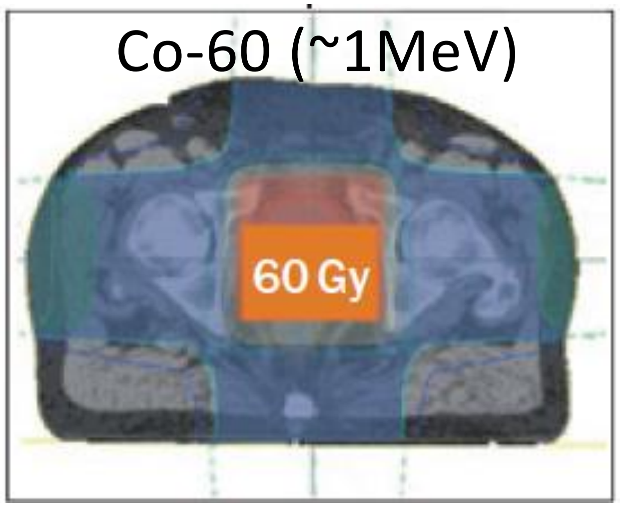
Electron 'build-up'
(skin sparing effect)

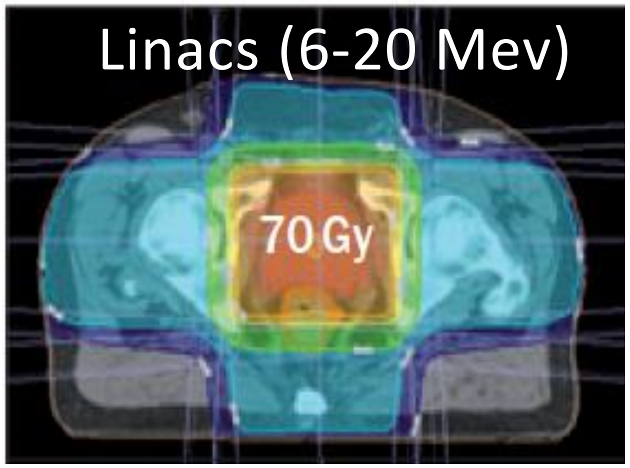
Exponential loss of photon
fluence (attenuation)

The importance of the electron build-up



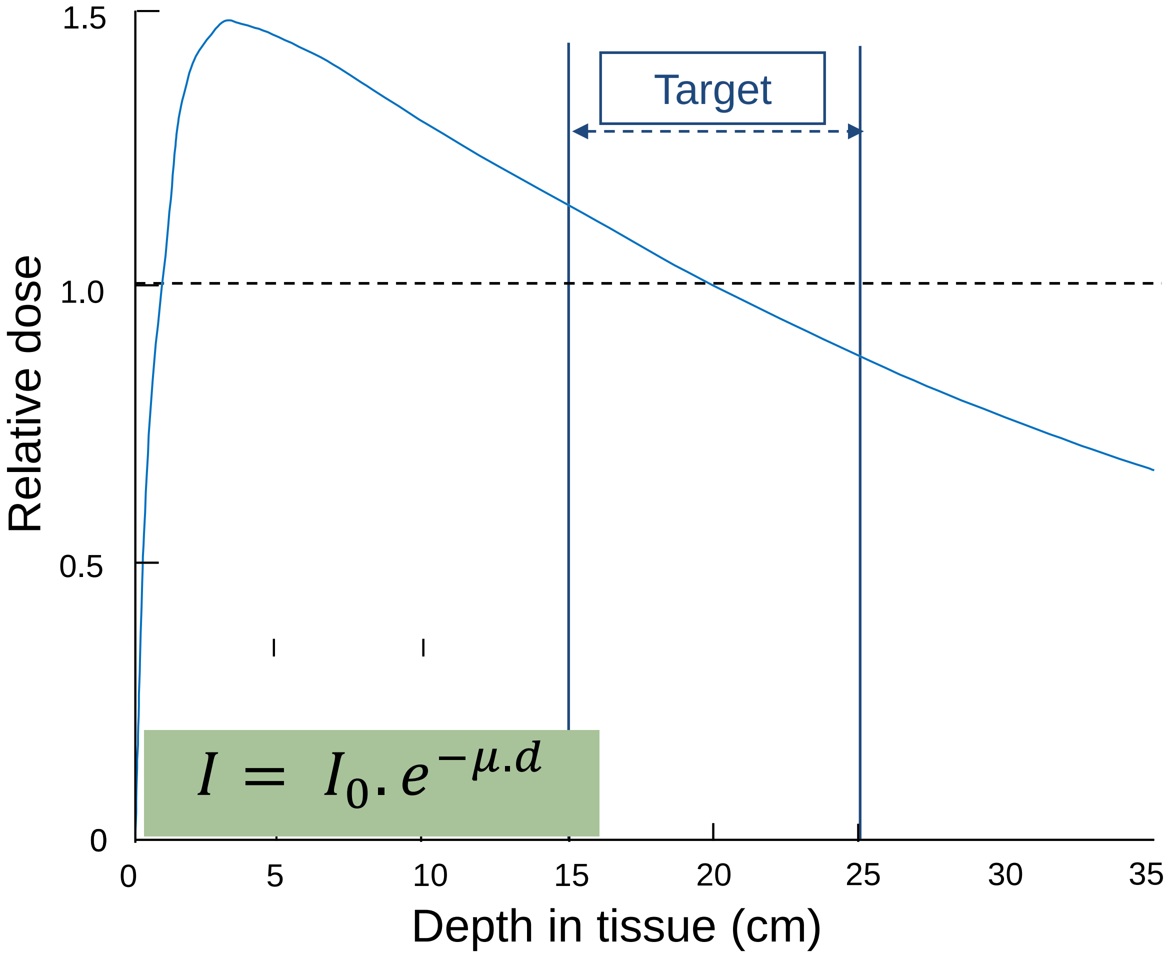

100-200 kV x-rays


Co-60 (~1MeV)


Linacs (6-20 Mev)

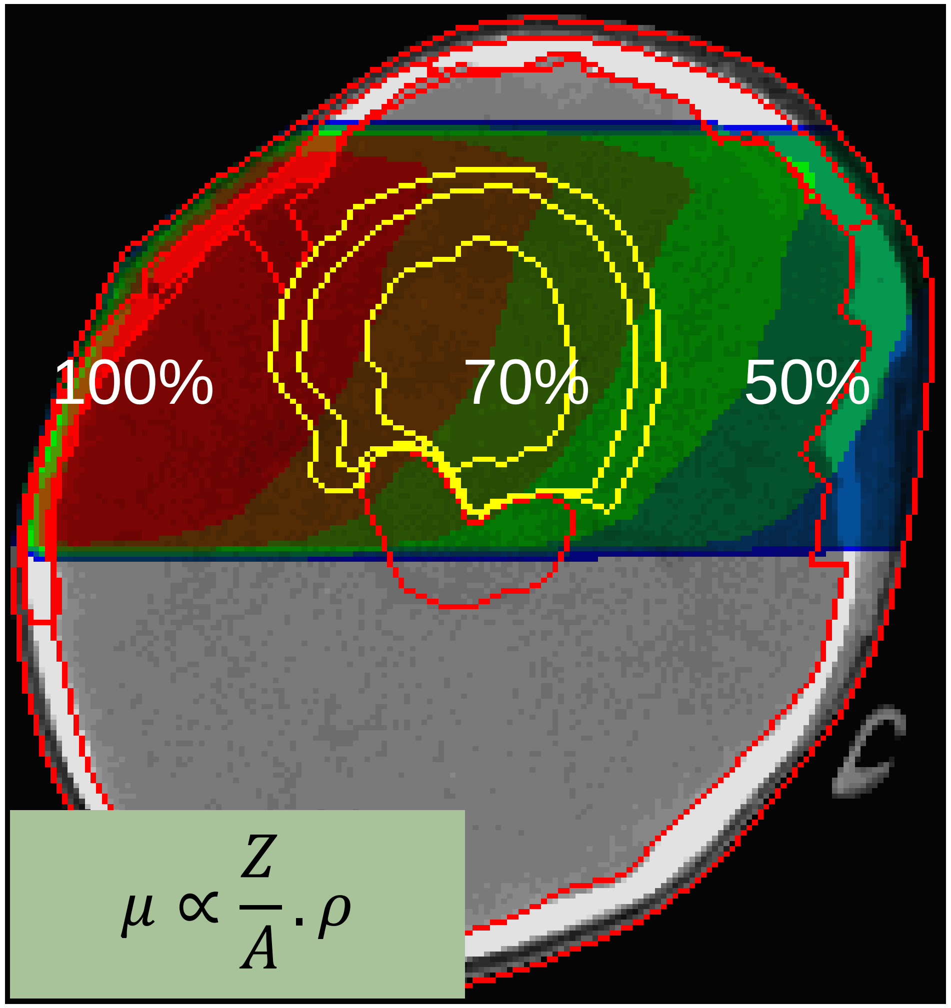
Photons in the patient (1)

Depth-dose curve for 15 MeV photons



$$I = I_0 . e^{-\mu . d}$$

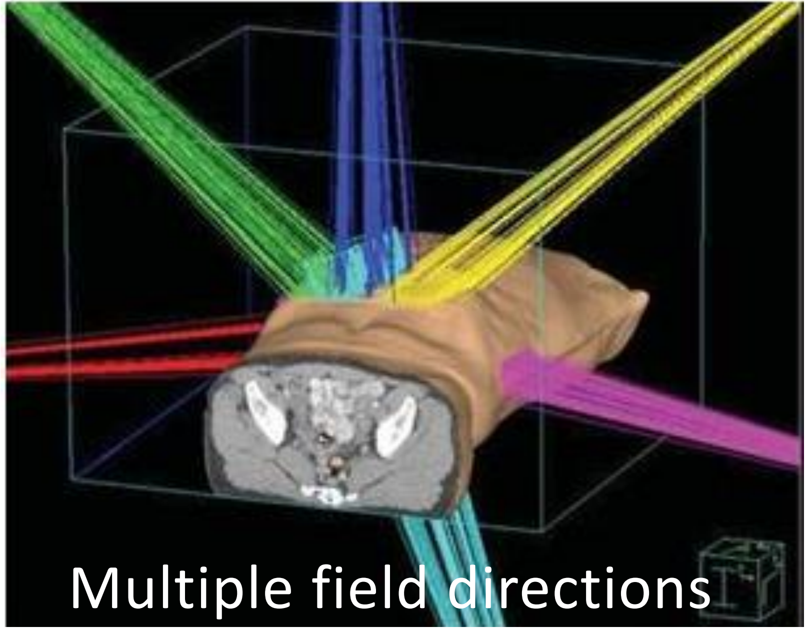
Dose distribution for 15 MeV photons



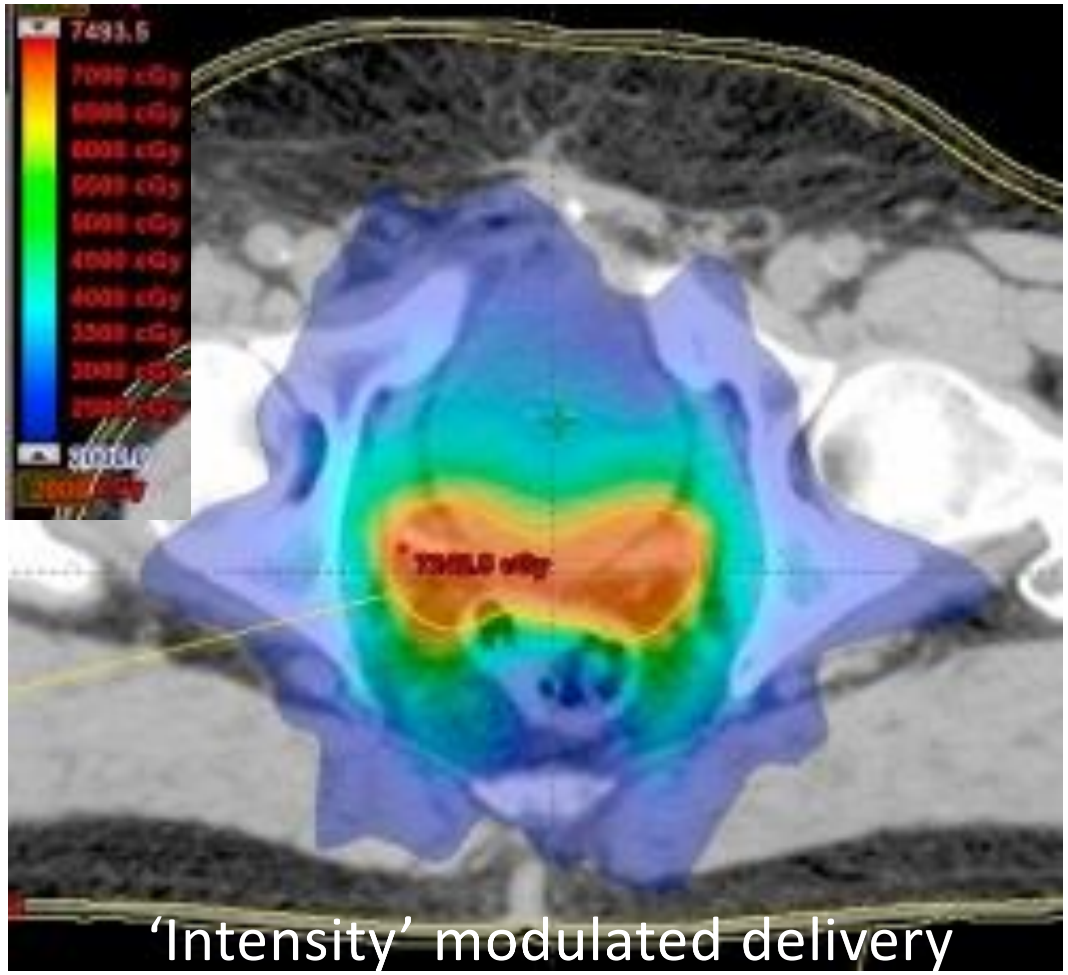
$$\mu \propto \frac{Z}{A} . \rho$$

Photons in the patient (2)

A modern ‘LINAC’ for radiotherapy

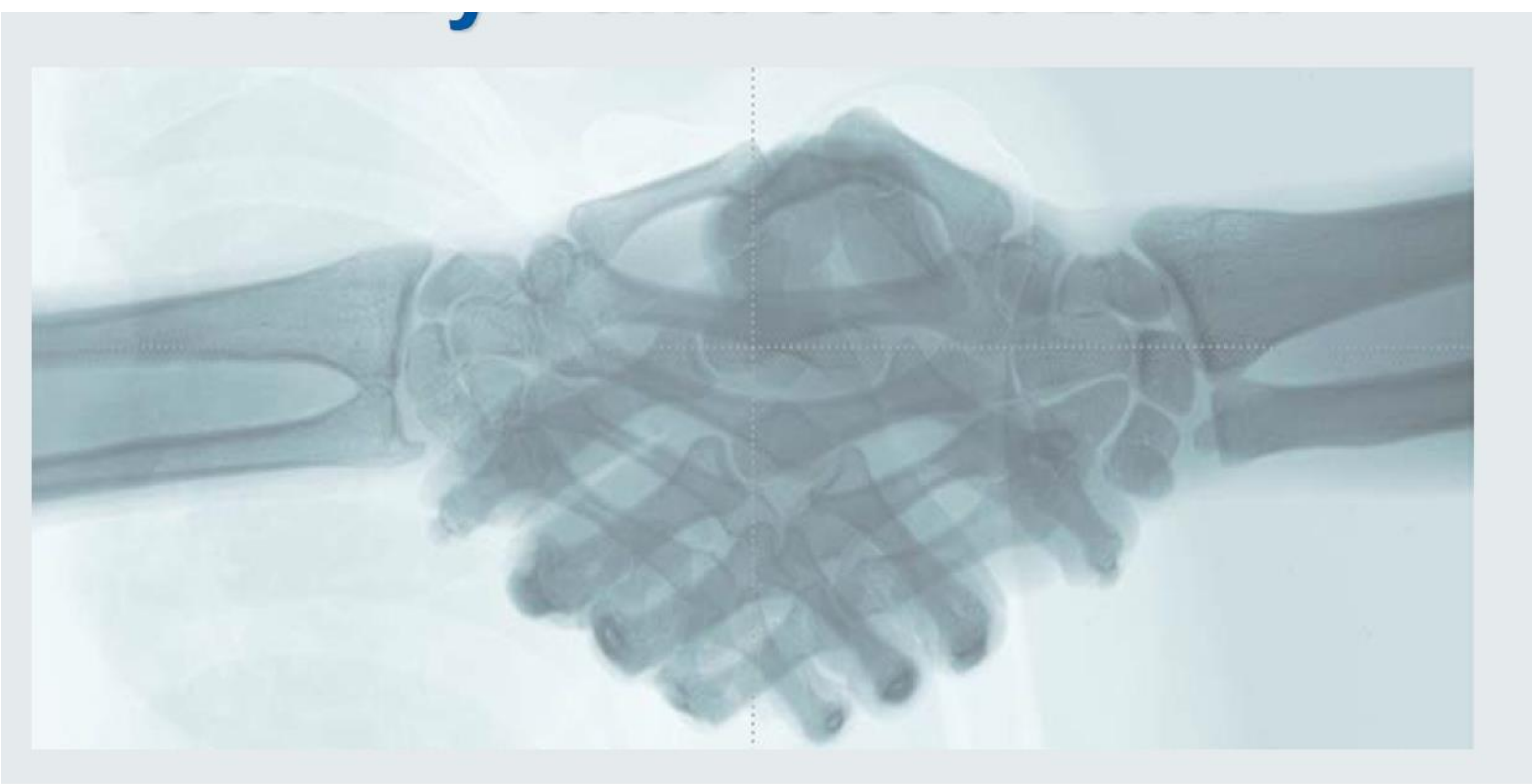


Multiple field directions



‘Intensity’ modulated delivery

Thanks for your attention



Literature:

- Dosimetrie ionisierender Strahlung, H. Reich, B.G. Teubner, Stuttgart, 1990
- Strahlenphysik, Dosimetrie und Strahlenschutz in zwei Bänden, B.G. Teubner, Stuttgart, 1992 (Bd.1) & 1997 (Bd. 2)
- Radiation Oncology Physics: A Handbook for Teachers and Students. E.B. Podgorsak, IAEA-Publication, 2005 (available via internet)
- http://de.wikipedia.org/wiki/Hauptseite

Course overview

Monday, 30th September

08:00-09:30 Basic physics	Prof. Tony Lomax
10:00-11:30 Delivery and verification	Dr. Nicolas Perichon
11:30-13:00 Lunch	
13:00-14:30 Imaging	PD D -Francois nd
15:00-16:30 Beam shaping	eider

Enjoy the rest of the course!

Tuesday, 01st

08:00-09:	Prof. Uwe Schneider
10:00-11:30	Prof. Tony Lomax
11:30-13:00 L	
13:00-14:30 Brachytherapy	Dr. Dario Terribilini
15:00-16:30 Radiation protection	Prof. Uwe Schneider
16:30-17:30 Tour of the department	*Optional*

Wednesday, 02nd October

08:00-09:30 Dosimetry	Dr. Jürgen Besserer
10:00-12:00 Special techniques	Prof. Tony Lomax & Prof. Raphael Moeckli