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Photon radiotherapy:
Photon interactions and characteristics

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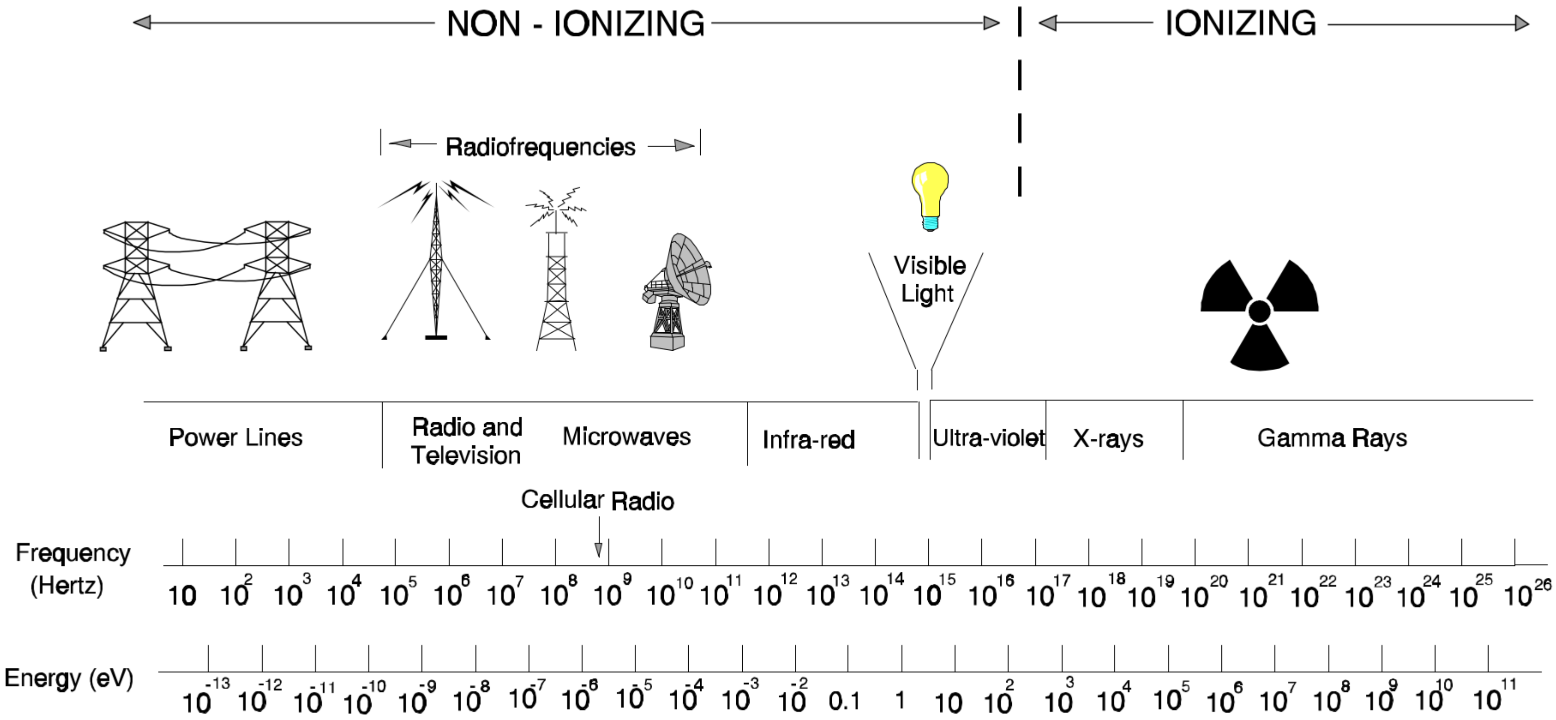
HIRO
Heidelberg Institute for Radiation Oncology
National Center for Radiation Research in Oncology Heidelberg
supported by:
German Cancer Research Center (DKFZ)
Heidelberg University Hospital
Heidelberg Ion-Beam Therapy Center (HIT)
Medical Faculty Heidelberg

DKTK German Cancer Consortium

Ionizing vs. non-ionizing radiation: photon energy



OET BULLETIN 56, Fourth Edition Aug. 1999

Office of Engineering and Technology, Federal Communications Commission, Washington, D.C.

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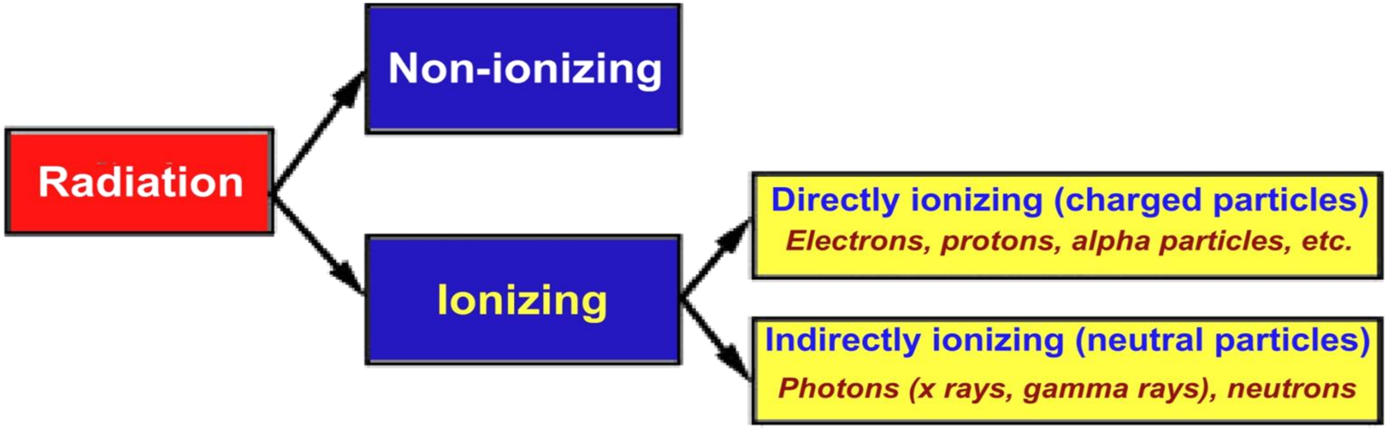
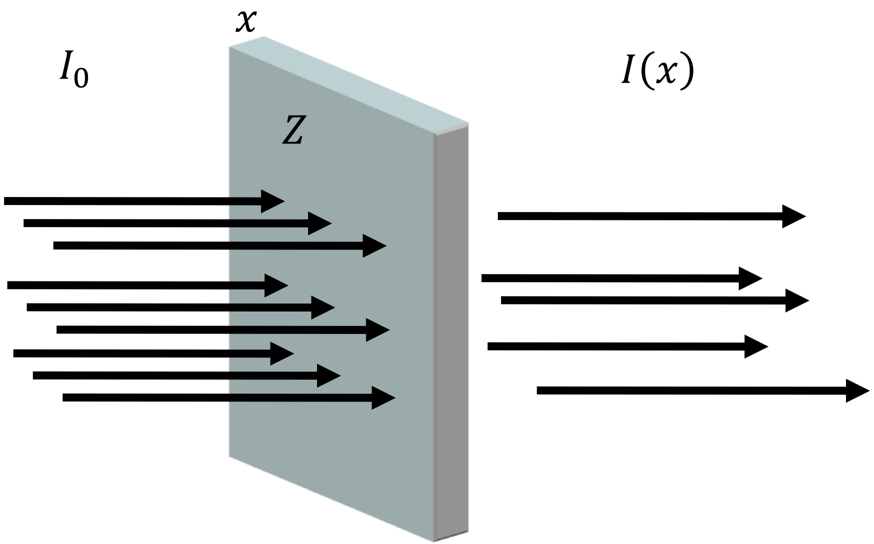
Directly vs. indirectly ionizing radiation



From: IAEA: Radiation Oncology Physics: A Handbook for Teachers and Students

Photon Interaction leads to Attenuation



Three possible interaction processes:

- Photoeffect τ
- Compton scattering σ
- Pair creation κ

Total absorption:

$$\mu = \tau + \sigma + \kappa$$

Lambert-Beer Attenuation Law:

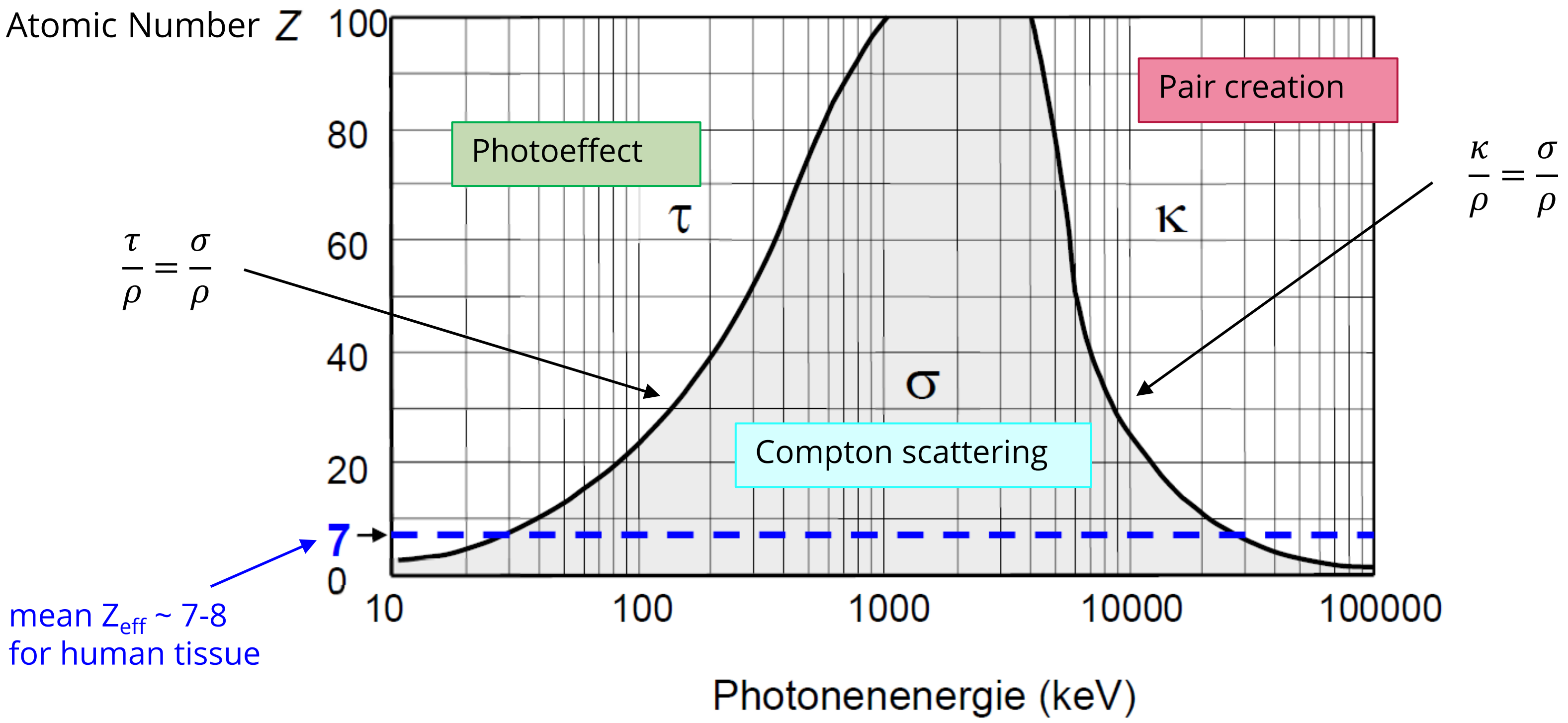
$$I(x) = I_0 \cdot e^{-\mu x}$$

Attenuation coefficient:

$$\mu \sim \frac{\text{Number of Interactions}}{\text{Pathlength}}$$

Photon Interaction with matter

3 processes: Dependency on Z and E_γ



H. Krieger: Grundlagen der Strahlungsphysik und des Strahlenschutzes, 7th Edition, Springer, 2023

Photoeffect

Photon interacts with electron of an inner atomic shell

→ Complete energy transfer of the photon to the electron

→ Electron is expelled, kinetic energy $E_k = E_\gamma - E_B$

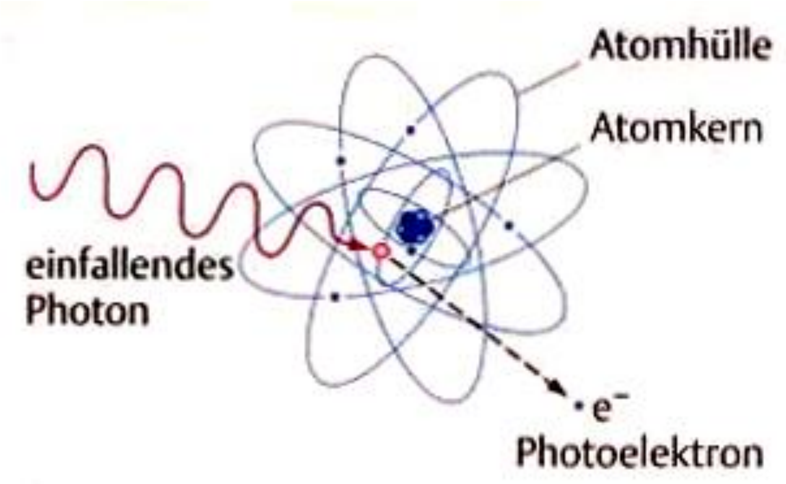


Photo-Absorption Dependency

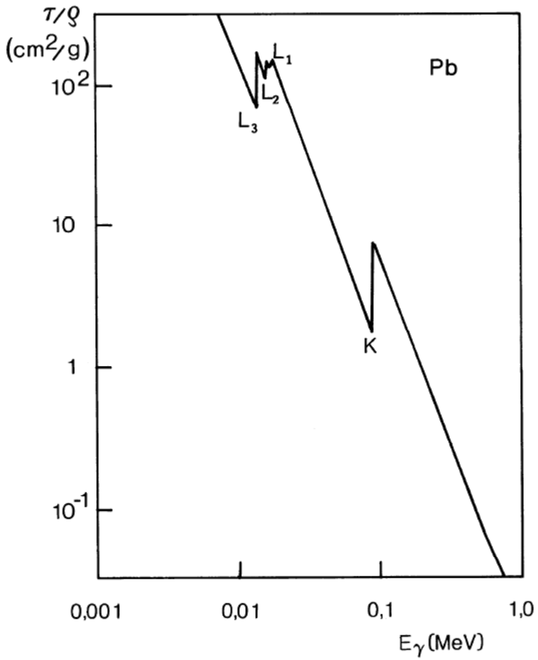
- On **photon energy**

$$\tau \sim \frac{1}{E_\gamma^3}$$

for $E_\gamma \ll 511\ keV$

$$\tau \sim \frac{1}{E_\gamma}$$

for $E_\gamma \gg 511\ keV$



Less absorption with higher energies

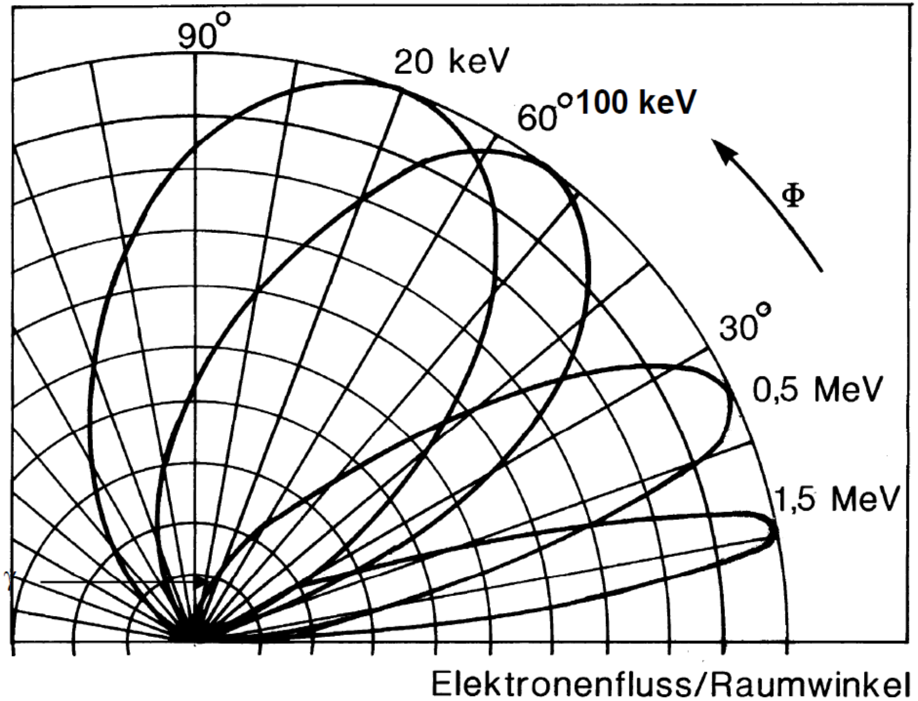
- On **atomic number** Z of the target

$$\tau \propto \rho \cdot \frac{Z^n}{A} \approx \rho \cdot \frac{Z^{4-4,5}}{A}$$

$\frac{Z}{A} \sim 0,5$ for lighter nuclei, $\sim 0,4$ for heavier nuclei

Higher absorption with higher Z → Radiation protection, collimators: Lead (Z=82), tungsten (Z=74), ...

Photoeffect: angular distribution of photoelectrons



→ With higher photon energy, photoelectrons are more forward directed

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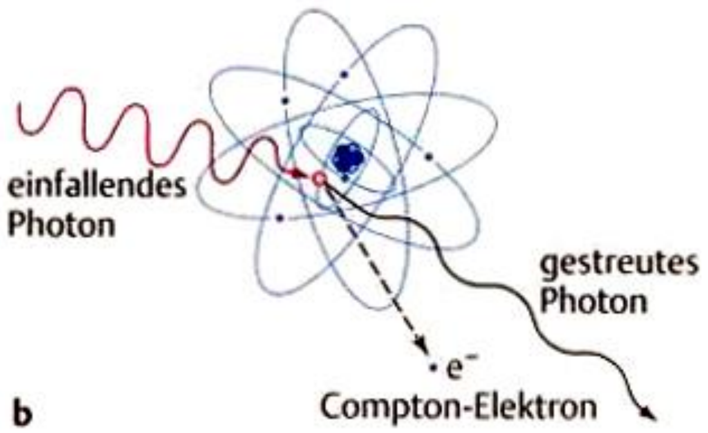
Compton Scattering

Collision between photon and electron of outer atomic shell

→ Incomplete energy transfer from the photon to the electron

→ Result: Electron + scattered photon $E_{\gamma'} < E_{\gamma}$



Greatest relative contribution on energy deposition for medical use of photon radiation

Almost independent of Z!

$$\sigma \sim \frac{Z}{A}$$

→ Reason for worse contrast in diagnostic X-Ray imaging with higher kV

Compton Scattering: relative energy of the scattered photon

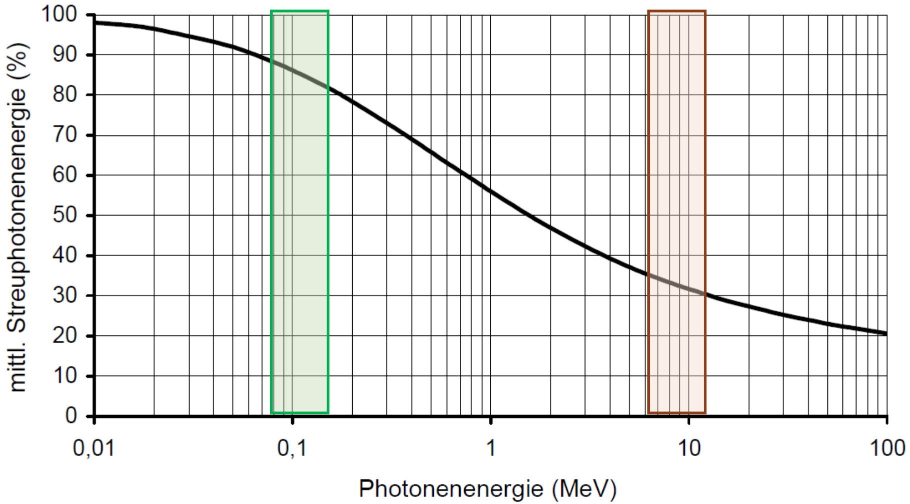
$$E_\gamma' = \frac{E_\gamma}{1+\frac{E_\gamma}{m_0 c^2}\cdot(1-\cos\phi)}$$

$E_\gamma \ll m_0 c^2 = 511\ keV$

Diagnostic X-Ray

$E_\gamma \gg m_0 c^2 = 511\ keV$

Therapeutic photons



	Diagnostic	Therapeutic
Energy of scattered photon	A little less than incoming photon	Much less than incoming photon
Energy transfer to electron	Small	Large
Scatter angle dependency of energy transfer	Low	High

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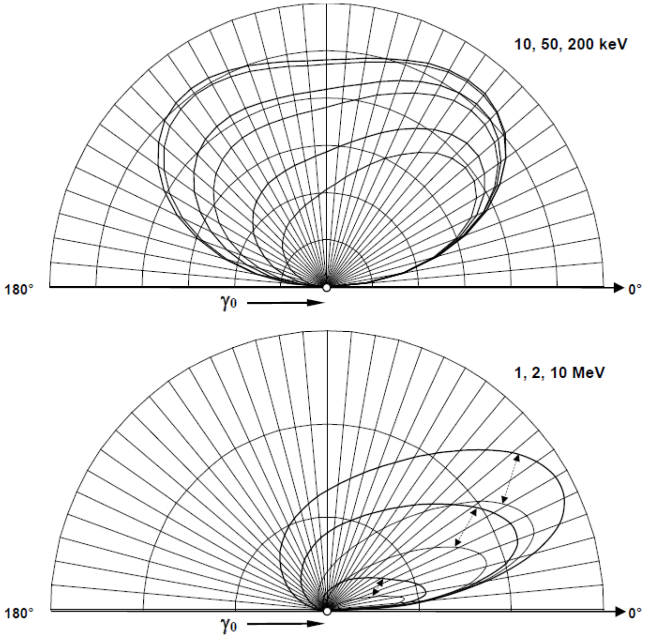
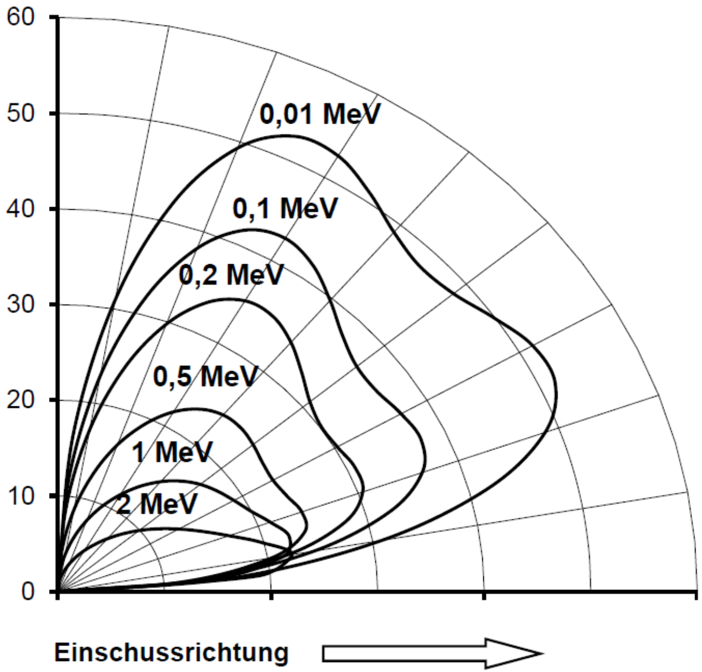
Compton Scattering: angular distributions

Scattered Photon



Compton Electron



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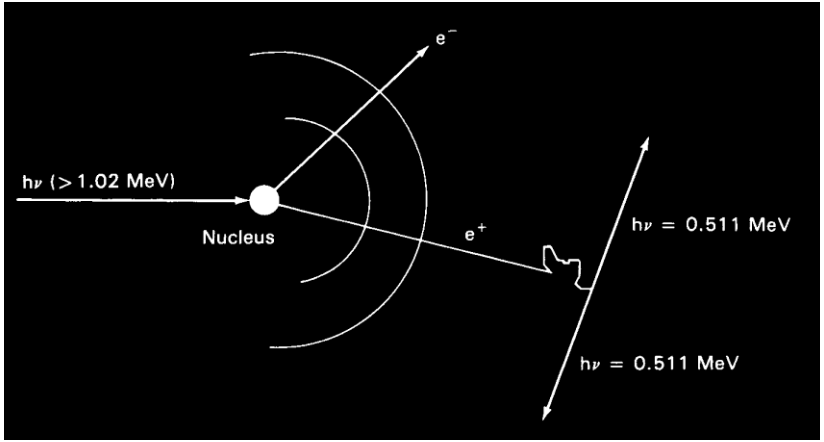
Pair creation

Photon energy is completely transferred into an electron – positron pair

Needs Coulomb field of an atomic nucleus: not possible in vacuum

Enegry threshold: $E_\gamma > 2\, m_0 c^2$ = 1.022 MeV



Secondary process: annihilation of e⁺ with another e⁻, emitted at 180°

$e^+ + e^- \rightarrow 2\gamma,\ E_\gamma = 511\,\mathrm{keV}$ (PET)

$\kappa_{paar} \propto Z \cdot \rho \cdot \log E_\gamma$

Weakly dependent on Z

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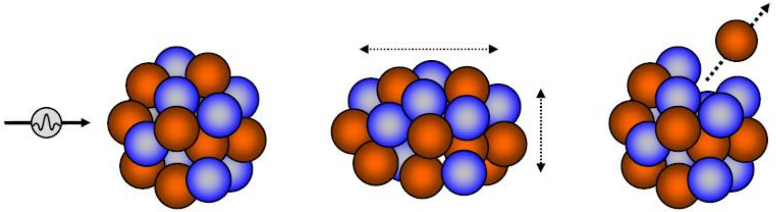
Nuclear photoeffect

Atomic Nucleus absorbs the photon → excitation → p or n emission



Energy threshold for lighter targets: above 10 MeV

Reaktion	Schwelle (MeV)	Tochternuklid	Zerfallsart	T½	E_γ (keV)
$^{12}C(\gamma,n)$	18,7	$^{11}C^*$	β+,EC	20,4 min	511
$^{14}N(\gamma,n)$	10,5	$^{13}N^*$	β+	9,96 min	511
$^{16}O(\gamma,n)$	15,68	$^{15}O^*$	β+,EC	122 s	511
$^{16}O(\gamma,2n)$	28,9	$^{14}O^*$	β+,γ	70,6 s	511,2313
$^{27}Al(\gamma,n)$	12,7	$^{26}Al^*$	β+,EC,γ	6,4 s	511,1810
$^{63}Cu(\gamma,n)$	10,8	$^{62}Cu^*$	β+,EC	9,73 min	511
$^{208}Pb(\gamma,n)$	7,9	^{207}Pb	stabil	-	-
$^{12}C(\gamma,p)$	16,0	^{11}B	stabil	-	-
$^{16}O(\gamma,p)$	12,1	^{15}N	stabil	-	-
$^{27}Al(\gamma,p)$	8,3	^{26}Mg	stabil	-	-
$^{63}Cu(\gamma,p)$	6,1	^{62}Ni	stabil	-	-
$^{208}Pb(\gamma,p)$	8,0	$^{207}Tl^*$	ß-	4,8 min	-

Does not happen for 6 MV Linacs

At Linacs with photon energies > 10 MV: can produce radioactive materials and is therefore a radiation protection concern

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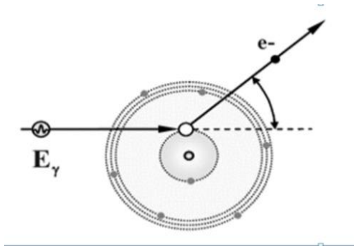
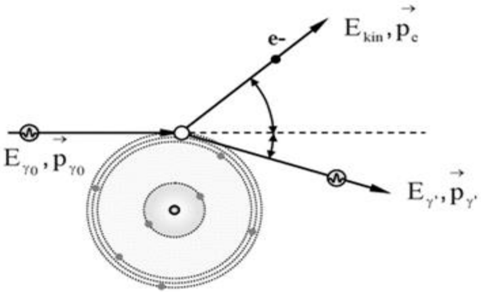
Interim Summary: photon interaction with matter

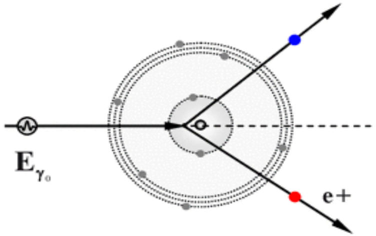
Photoeffect

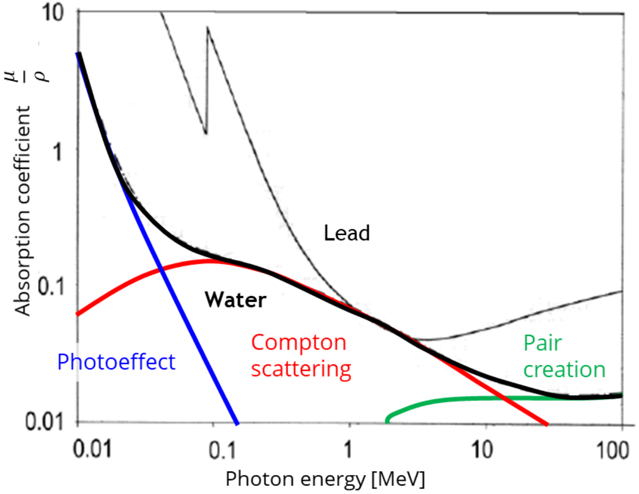


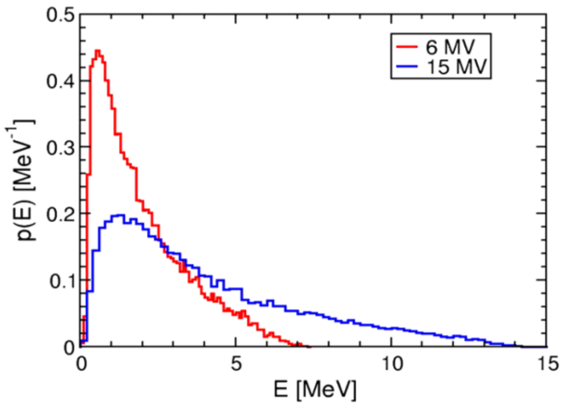
Compton scattering



Pair creation







Photonen-Bremsstrahlungs-Spektrum
eines Linearbeschleunigers

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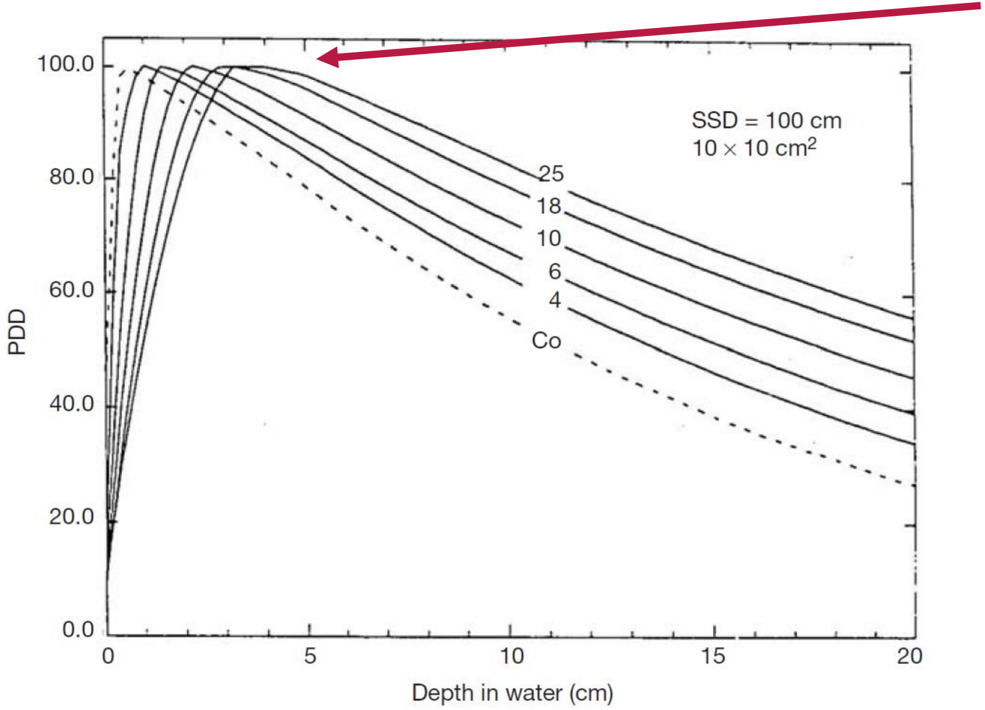
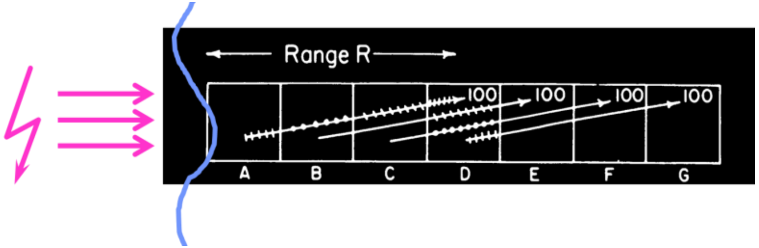
Photon depth dose curves



Build-up region:

Build-up of secondary electron equilibirum



- Secondary e^- are forward directed
- Much less secondary e^- in air than in water

IAEA: Radiation Oncology Physics: A Handbook for Teachers and Students

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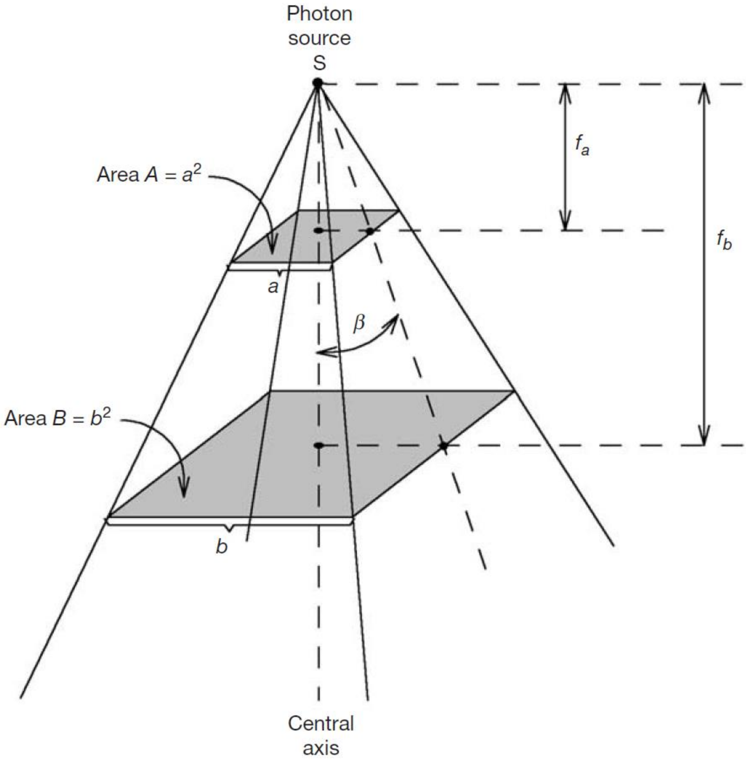
Some terminology: divergent photon beam



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Photon fluence

$$\phi = \frac{dN}{dA}$$

=Number of photons that enter a cross-sectional area dA

Energy fluence

$$\Psi = \frac{dE}{dA}$$

=Amount of energy crossing a unit area dA

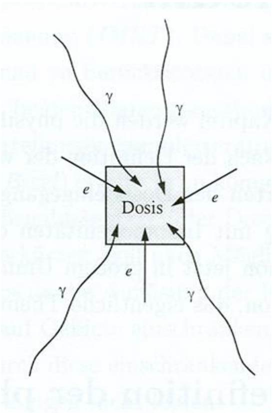
Inverse square law

$$\frac{\phi_A}{\phi_B} = \frac{B}{A} = \frac{b^2}{a^2} = \frac{f_b^2}{f_a^2}$$

The photon fluence is inversely proportional to the square of the distance from the source

Some terminology

Absorbed dose [Gy]

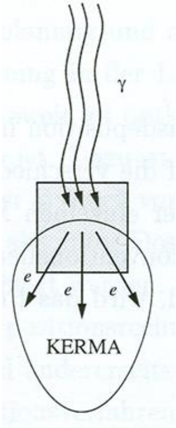


$$D = \frac{d\bar{\varepsilon}}{dm} = \frac{1}{\rho}\frac{d\bar{\varepsilon}}{dV}$$

$\bar{\varepsilon}$: mean Energy absorbed in the mass element dm

KERMA [Gy]

Kinetic **E**nergy **R**eleased in **Ma**terial

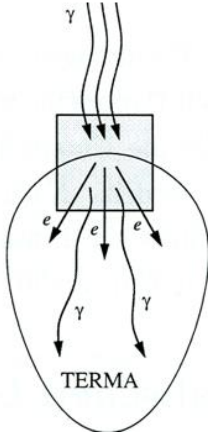


$$K = \frac{dE_{tr}}{dm} = \frac{1}{\rho}\frac{dE_{tr}}{dV}$$

E_{tr} : Energy transferred to **secondary electrons** within the mass element dm

TERMA [Gy]

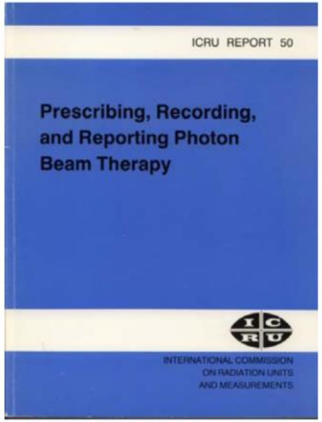
Total Energy **R**eleased in **Ma**terial

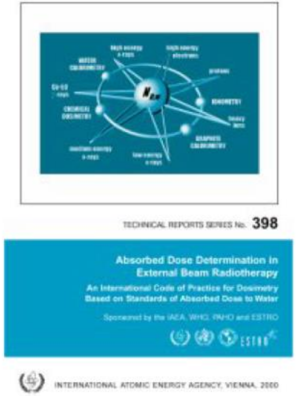


$$T = \frac{dE}{dm} = \frac{1}{\rho}\frac{dE}{dV}$$

KERMA plus Energy of the photons exiting the mass element

Absorbed dose





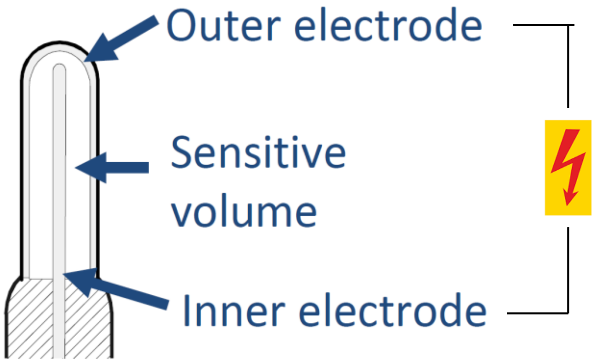
The generally accepted quantity measured to predict the effect of radiation therapy is the

Absorbed Dose to Water *D*

$$D = \frac{\text{Energy Absorbed [J]}}{\text{Mass of Absorber [kg]}} \quad \text{[Gy]}$$

Dose measurement with ionization chambers

Determination of absorbed dose (to water!) with an air-filled ionization chamber



Theoretical calculation:

$$D = \frac{\text{Charge measured}}{\text{Air Mass}} \cdot \text{Energy to produce an ion pair} \cdot \text{Conversion factor (air to water)}$$

In practice:

Calibration of chambers in ^{60}Co beams (reference beam quality) by a

Primary / secondary standard dosimetry laboaratory (water calorimetry)

$$D = \text{Charge measured} \cdot \text{Chamber calibration factor (dose in water)}$$

Practical dosimetry: correction factors

Dosimetry protocols: AAPM TG-51, IAEA TRS-398, DIN 6800-2, NCS-18, …

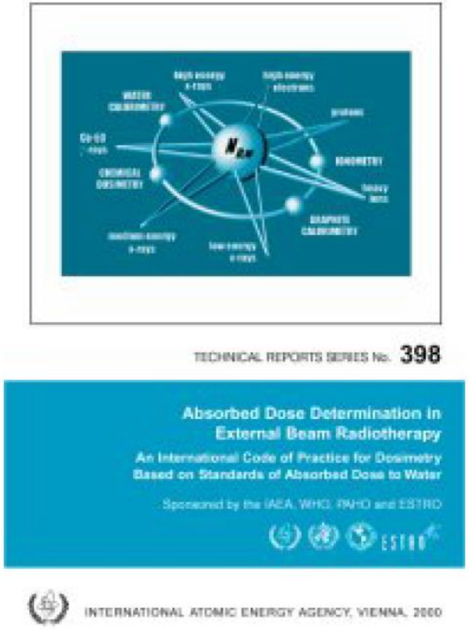
$D_{w,Q} = M_Q N_{D,w,Q_0} k_{Q,Q_0}$ with

$D_{w,Q}$: absorbed dose to water

M_Q : corrected reading of the dosimeter in beam quality Q

N_{D,w,Q_0}: absorbed-dose-to-water calibration coefficient at Q_0 (^{60}Co)

k_{Q,Q_0} : beam-quality correction factor



Additional correction factors for:

- Chamber properties, air pressure and temperature
- Non reference-conditions (small fields, plan-specific, …)
- Magnetic fields (MR-Linacs)
- …

Practical dosimetry with ionization chambers

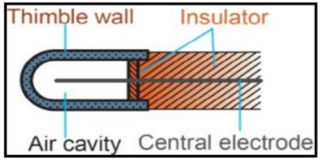
Different ionization chamber types in clinical use, just some examples:

www.ptwdosimetry.com

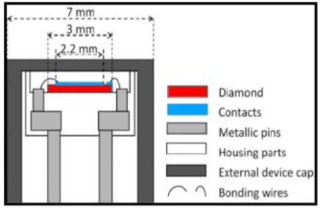
→ Numerous other models and types out there,
for lots of different reasons / use cases

Choice of the right detector

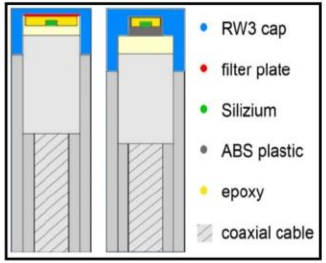
- **Luftgefüllte Ionisationskammern**



- **Synthetischer Diamant**



- **Dioden**



Detektortype	PTW Semiflex 31010	PTW Semiflex 31016
Nominales Messvolumen [cm³]	0,125	0,016
Messvolumendichte [g.cm^{-3}]	1,225 x10^{-3}	1,225 x10^{-3}
Dimensionen des Messvolumens	Radius: 2,75 mm Länge: 6,5 mm	Radius: 1,45 mm Länge: 2,9 mm
Anwendungsfelder (laut der Hersteller)	3x3 cm² bis 40x40 cm²	2x2 cm² bis 30x30 cm²
Betriebsspannung [V]	400	400

Detektortype	PTW E-Diode 60017 (nicht geschirmte Diode)	PTW P-Diode 60016 (geschirmte Diode)	PTW microDiamond 60019
Nominales Messvolumen [mm³]	0,03	0,03	0,004
Messvolumendichte [g.cm^{-3}]	2,32	2,32	3,51
Dimensionen des Messvolumens	Radius: 0,56 mm Dicke: 30µm	Radius: 0,56 mm Dicke: 30µm	Radius: 1,1 mm Dicke: 1µm
Anwendungsfelder (laut der Hersteller)	1x1 cm² bis 10x10 cm²	1x1 cm² bis 40x40 cm²	1x1 cm² bis 40x40 cm²
Betriebsspannung [V]	0	0	0

Absolute vs. Relative Dosimetry

Water tank

www.iba-dosimetry.com

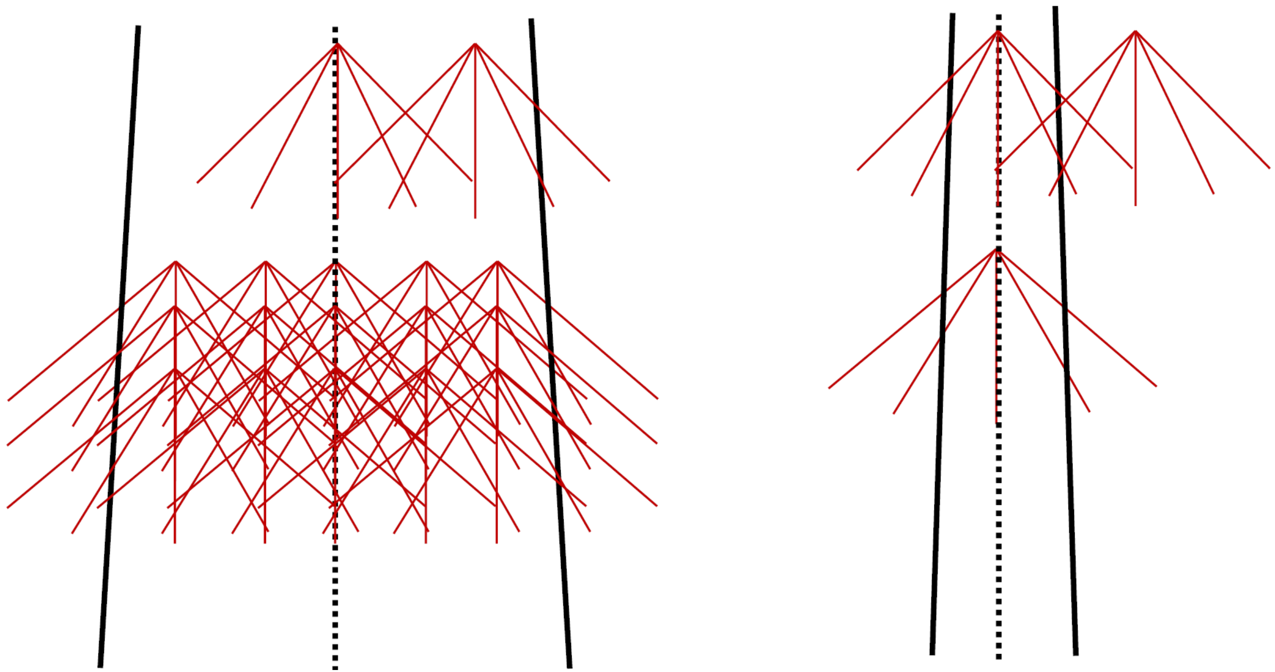
Both performed in a water tank, but….

Absolute dosimetry:
Determination of a point dose under reference conditions and calibration of the Linac monitor chamber

Relative dosimetry:
Measurement of dose profiles that characterize the treatment beam of a linac

Small photon fields

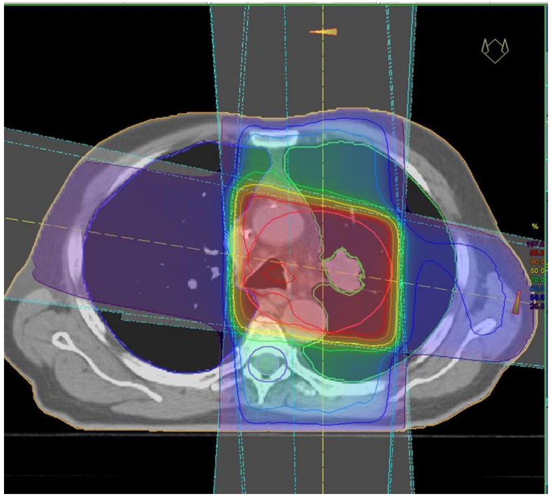
- A photon treatment field can be considered small if no lateral charged particle equilibrium is present on the central axis any more
- “outside” directed electron transport dominates



Dose calculation

Remember: With photons, you have

- Indirect ionization
- Scattering
- Secondary electrons



→ Need a model for the dose spread after a primary interaction

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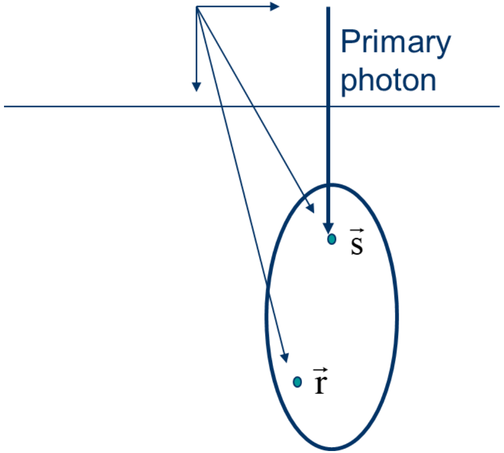
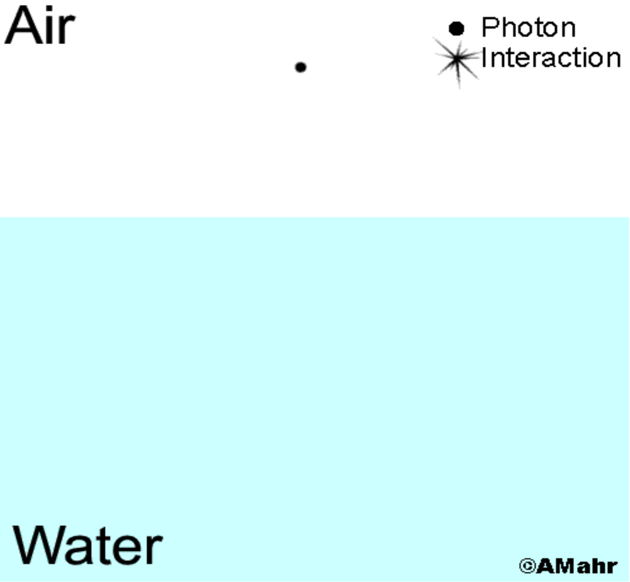
Dose calculation: point spread kernel

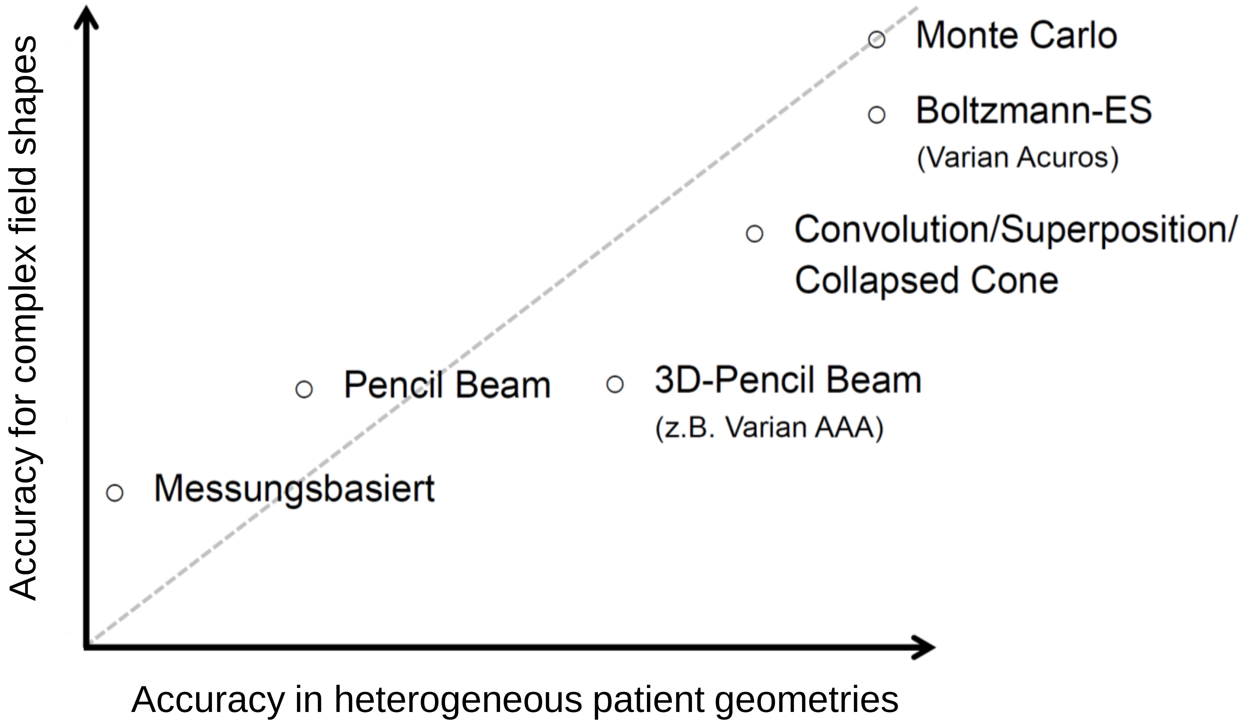




Kernel of dose spread $k|\vec{r}-\vec{s}|$

→ Dose deposition in voxel $\vec{r}$ caused by photon interaction in voxel $\vec{s}$

Dose calculation algorithms



(by courtesy of Markus Alber)

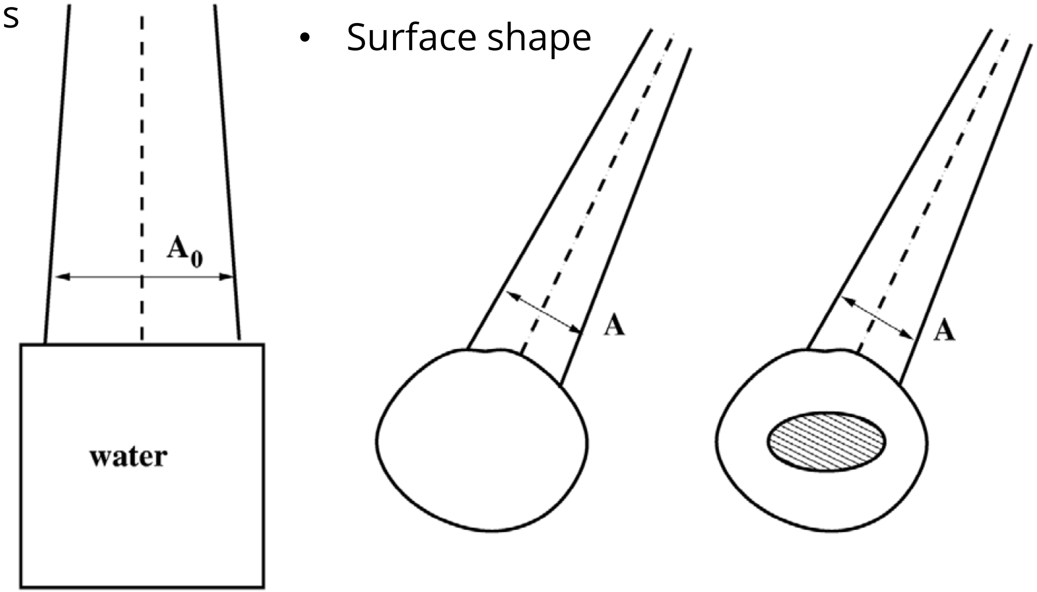
Measurement based dose calculation

Tabulation of measurements in a water tank for different field sizes

Corrections for

- Field shape
- Distance
- Surface shape

Corrections for density inhomogeneities



$D_W(A_0,x,y,z) \longrightarrow D_{hom}(A,x,y,z) \longrightarrow D(A,x,y,z)$

(by courtesy of Markus Alber)

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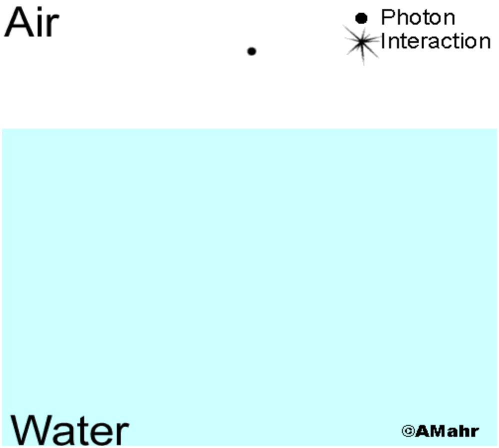
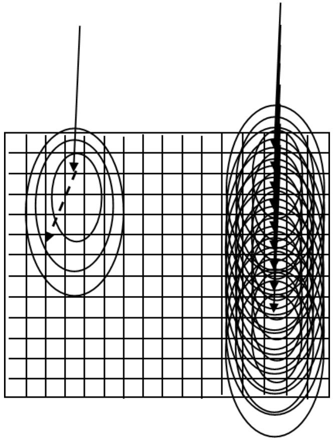
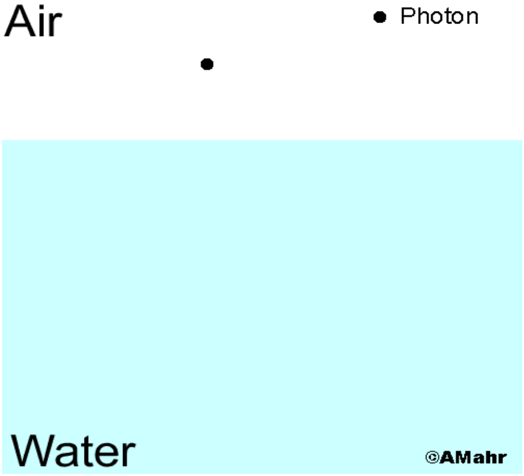
Pencil beam dose calculation

Pre-calculation of absorbed dose along central axis for “pencil” beam





Dose calculation for broad beam: superposition of pencil beams



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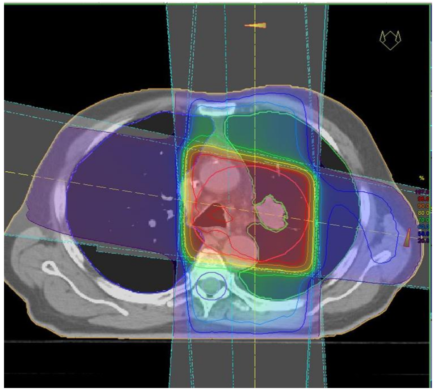
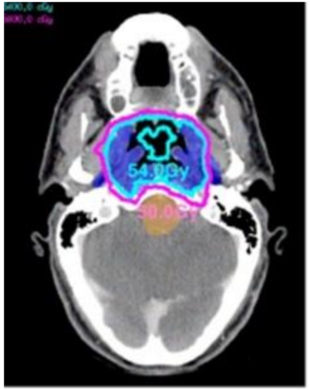
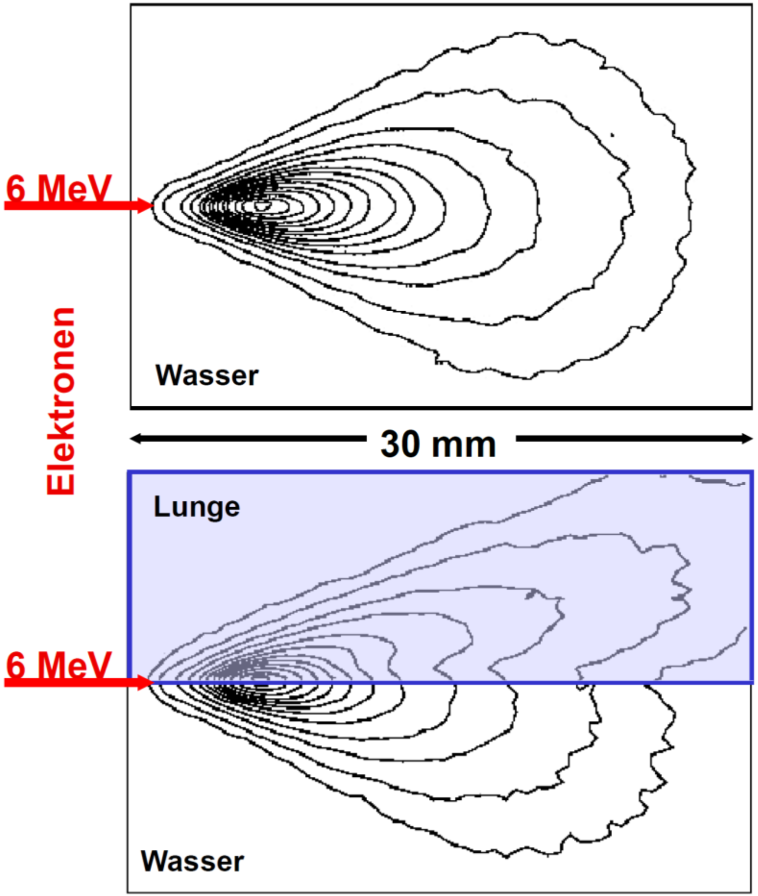
Inhomogeneity correction





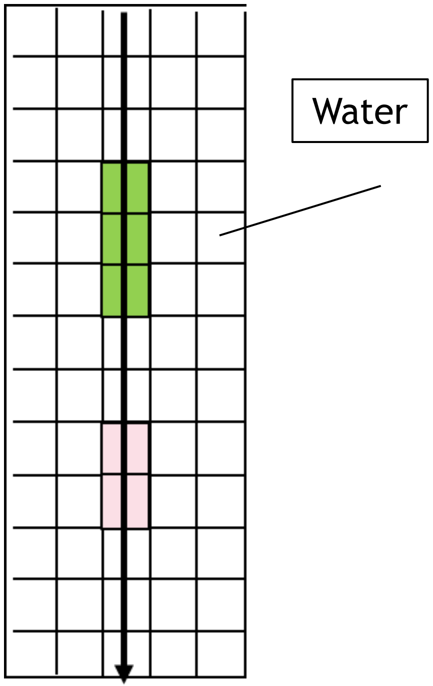


(by courtesy of Markus Alber)

Inhomogeneity correction: Pencil Beam

Water equivalent depth

→ pencil beam kernel stretching with inverse mean density

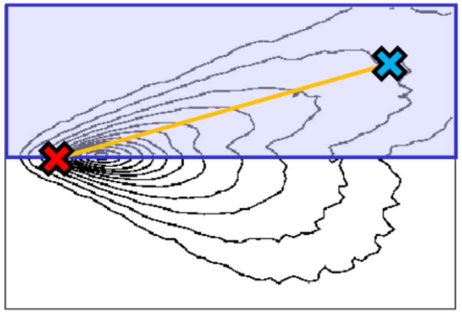


$$d_{rad} = d \cdot \frac{\overline{\rho}_e}{\rho_{e,H_2 0}}$$

Inhomogeneity correction: Collapsed Cone

Collapsed cone dose calculation:

Kernel based algorithms

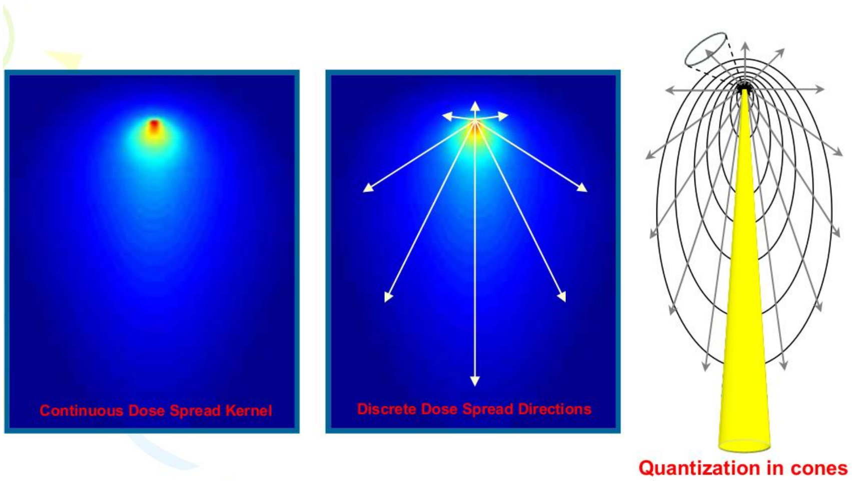


1) Calculate mean density along the line
2) Stretch kernel according to inverse mean density

(by courtesy of Markus Alber)

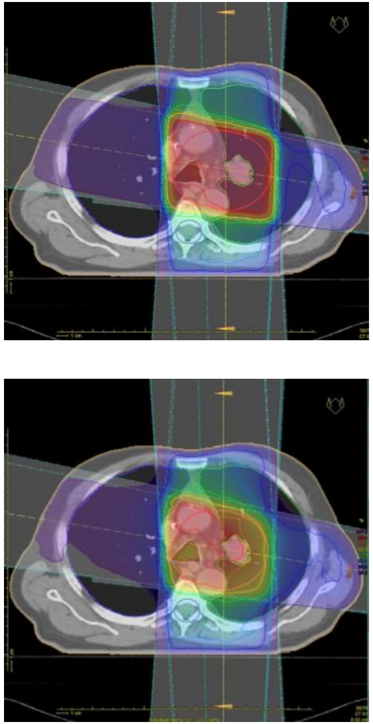
"Collapsed" cone:

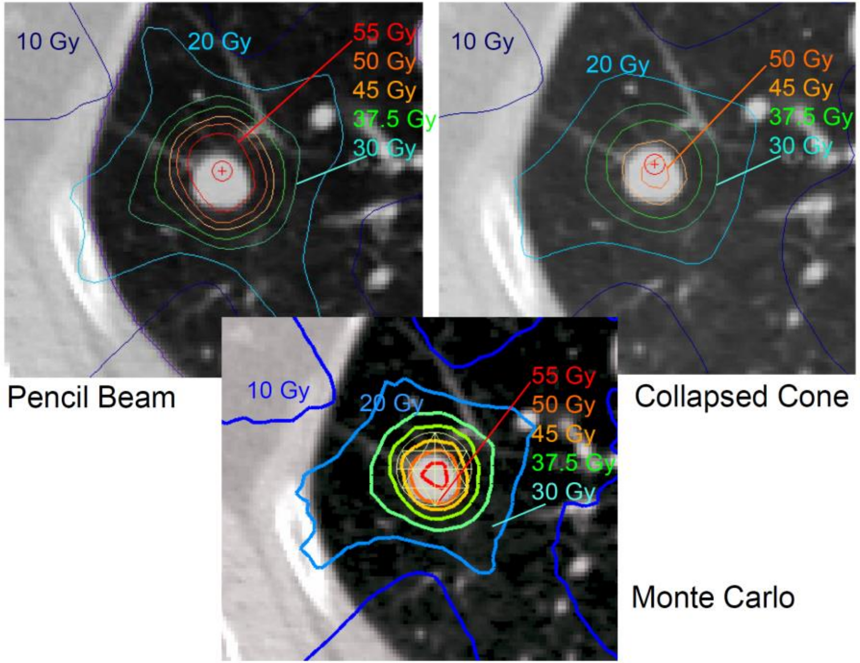
Density correction along central line is representative for one sector / cone



Pencil beam vs. Collapsed cone dose calculation

Pencil beam overestimates tumor dose in the lung





(by courtesy of Markus Alber)

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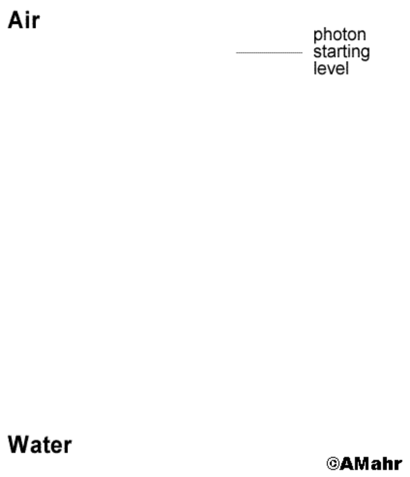
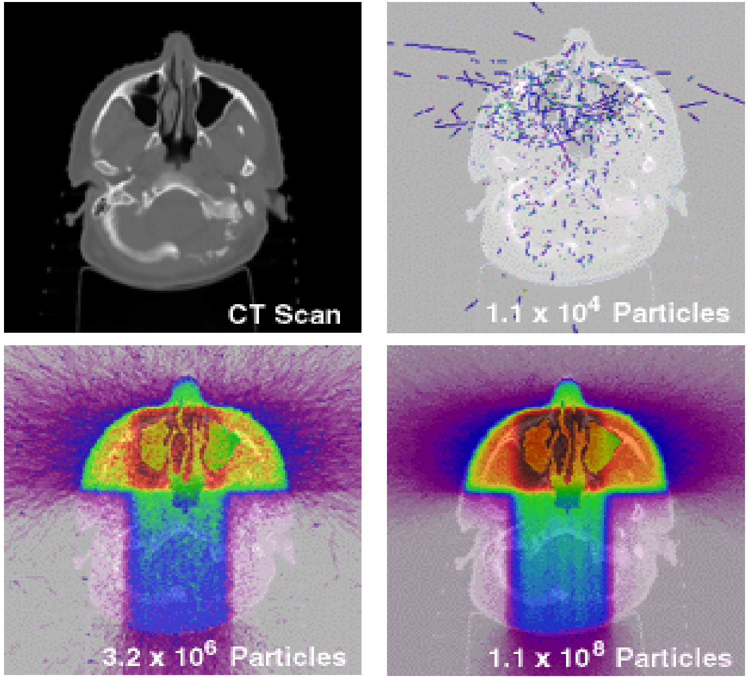
Monte Carlo dose calculation

Simulation of stochastic nature of photon interactions





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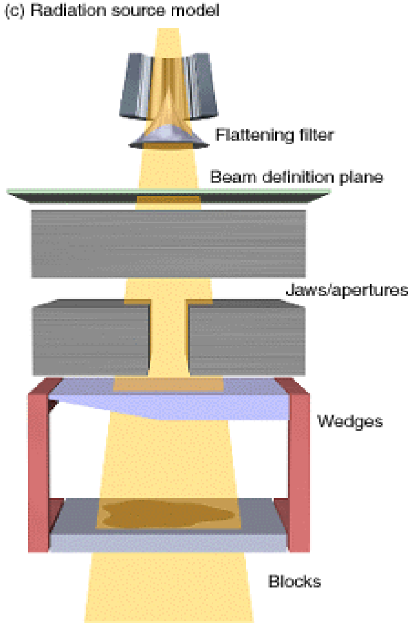
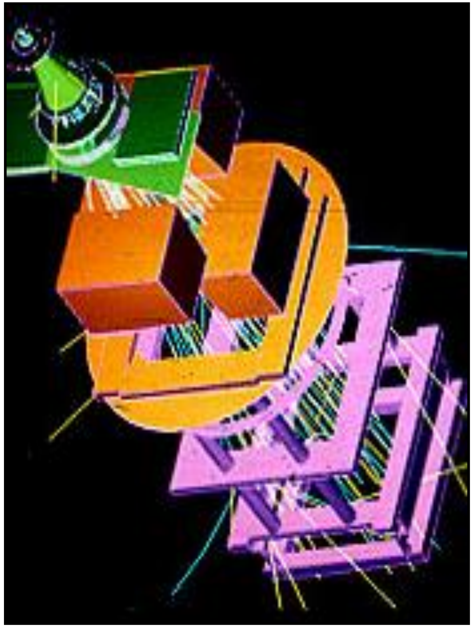
Monte Carlo simulation

Full Monte Carlo Linac Simulations need a lot of details, need to model all elements of the treatment head with high detail

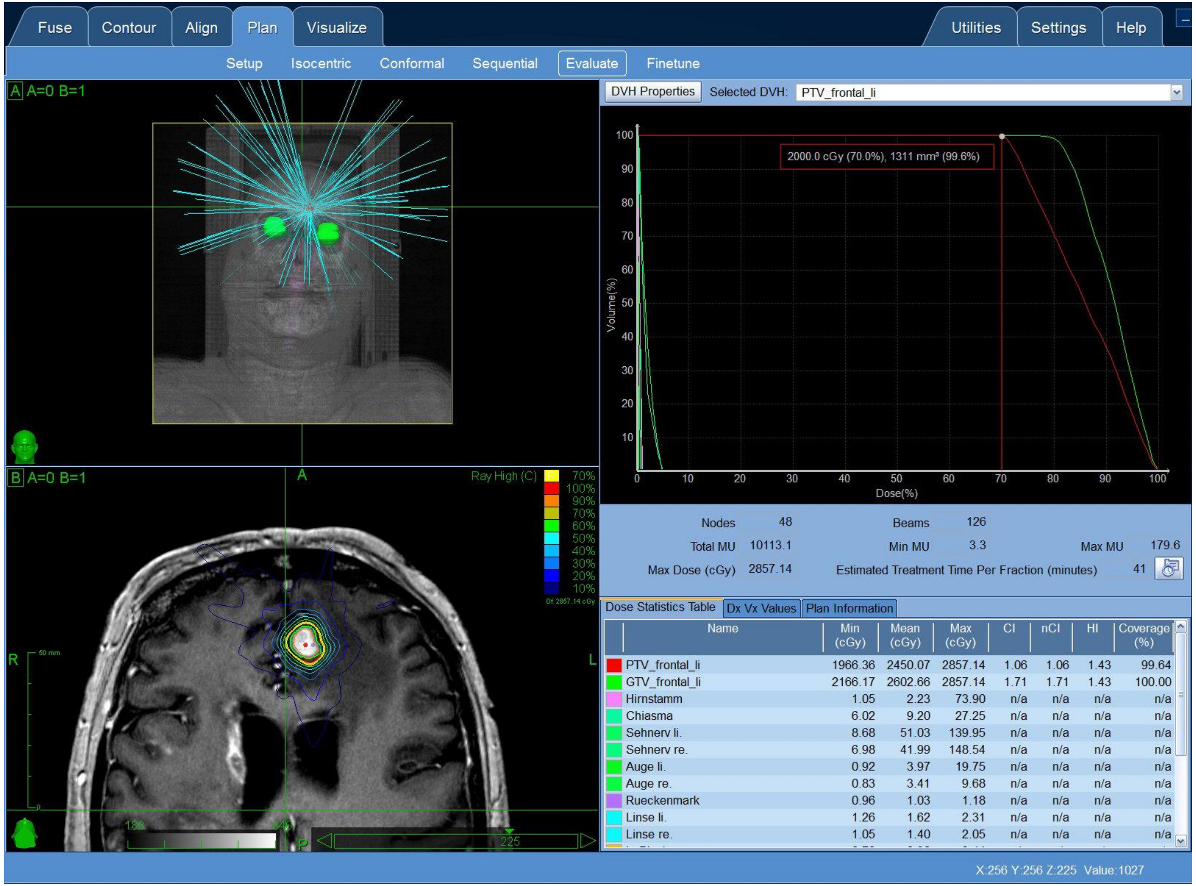




Alternative: pre-calculated phase space,

Full simulation starts at a certain point, for example before the Multi-Leaf Collimator, or in the patient

Do you always need Monte Carlo?



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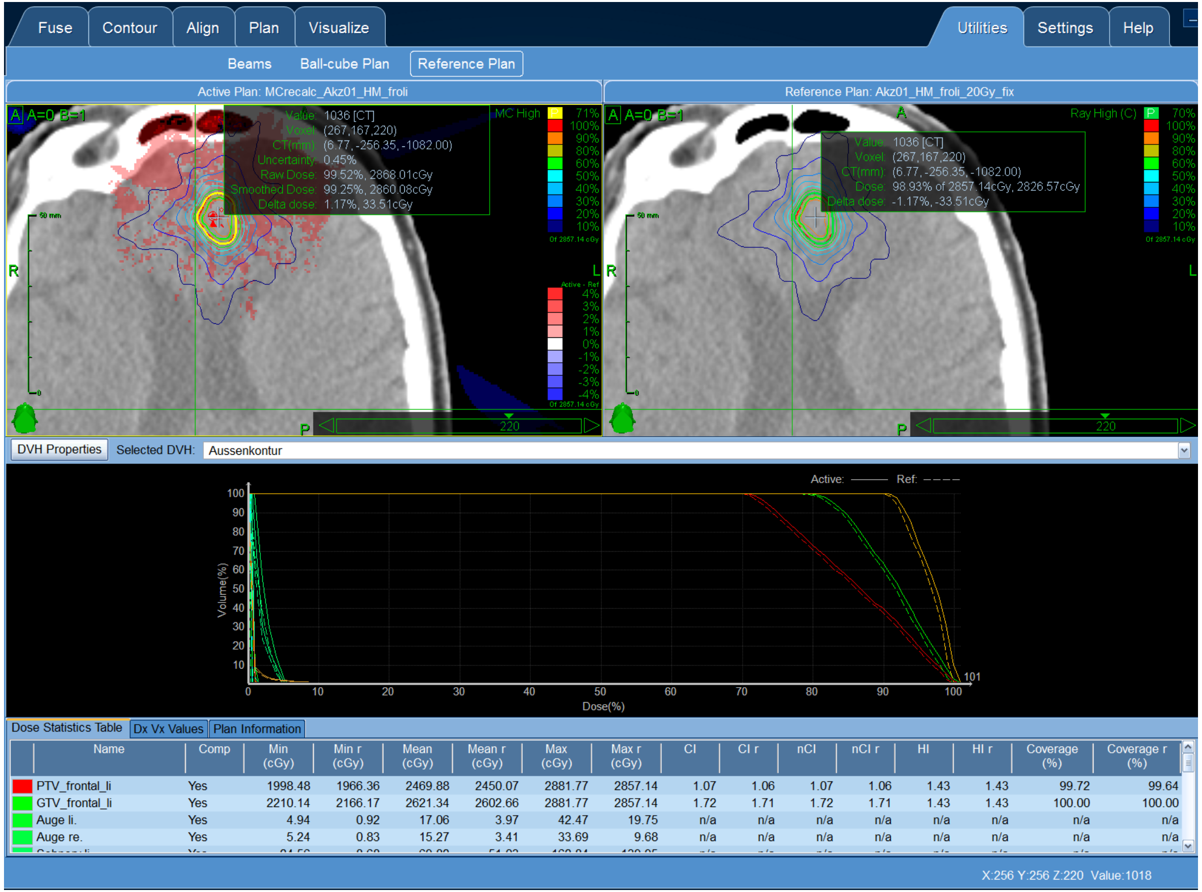
Do you always need Monte Carlo?



Here:
very simple, measurement based dose calculation

Shape of the dose distribution is defined by <u>irradation geometry</u> of many thin „needle“ beams

No clinically relevant difference (in homogeneous areas of the body, i.e., intracranial)

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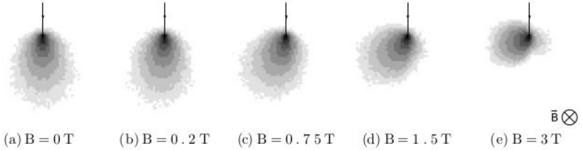
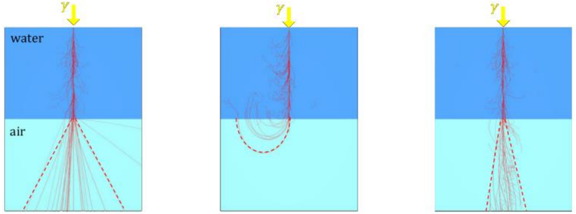
Do you always need Monte Carlo?

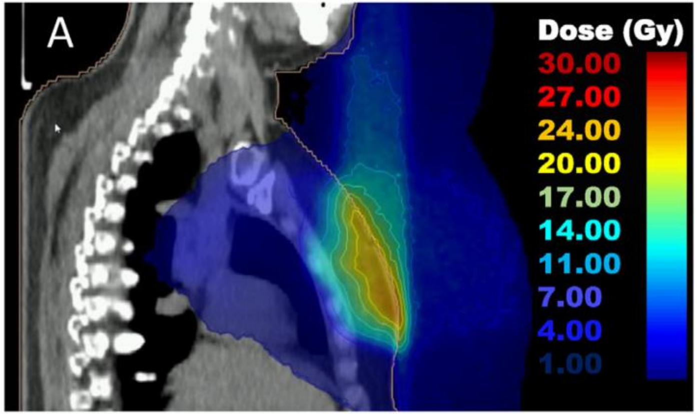
MR-Linac: static magnetic field deflects secondary electrons



AJE Raaijmakers et al., Phys. Med. Biol. 2008



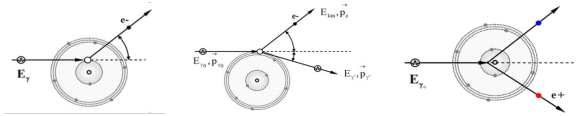
courtesy of O Schrenk, DKFZ Heidelberg

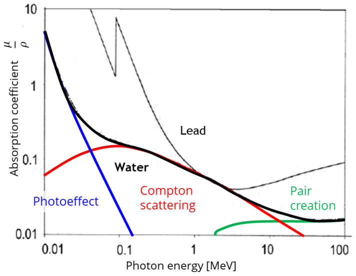


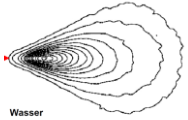
M. Nachbar et al. / Radiotherapy and Oncology 145 (2020) 30–35

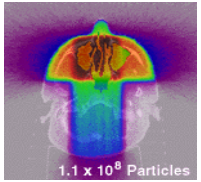
Summary

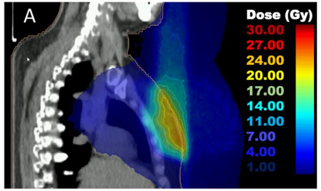
- Interactions of high energy photons with matter
- Attenuation
- Dose deposition: secondary electrons
- Depth dose curves
- Dose quantities
- Dose measurement
- Models of dose deposition: dose calculation











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