The Physics of Charged Particle Therapy

Monte Carlo Particle Transport in Medical Physics

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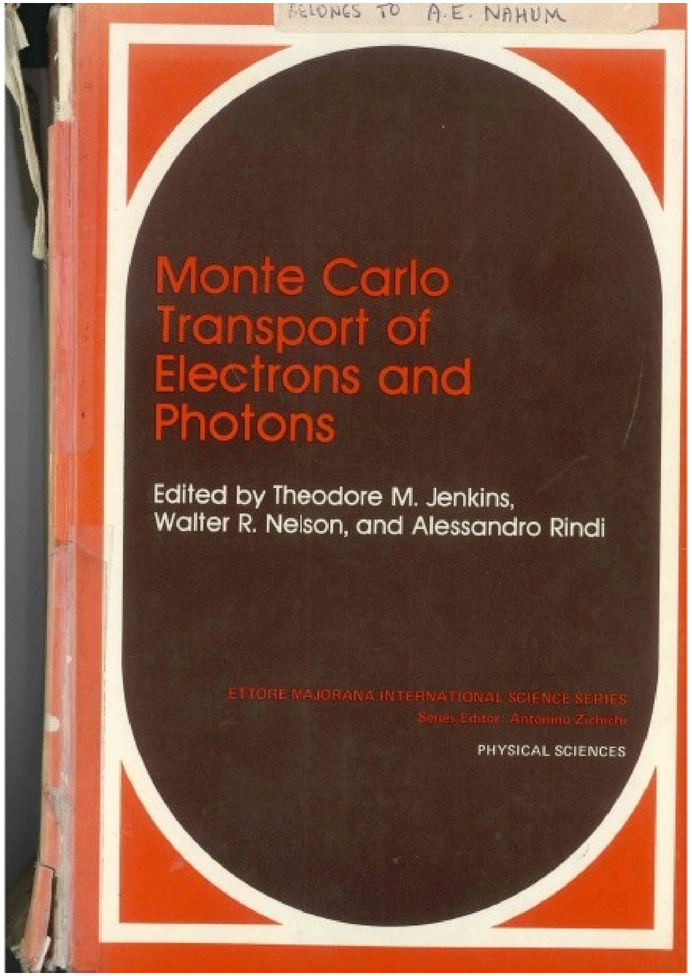
Outline

- Examples of Monte Carlo Applications in Medical Physics
- Monte Carlo for Accurate Dose Calculations
  - Dose Calculation in Treatment Planning Systems
    - Experiment-based Algorithms
    - Analytical Algorithms
    - The Problem of Interfaces
    - Monte Carlo Dose Calculation
- Examples of Monte Carlo Treatment Head/Beam Modeling
- Monte Carlo Modeling in Magnetic Field – MR-guided Radiotherapy
- Monte Carlo-based Treatment Planning
  - Calculation Time vs Statistical Noise
- Monte Carlo Modelling of Radiation Quality

Examples of Applications in Medical Physics

- Treatment head modeling
- Beam delivery/beam characteristics
- Dosimetry
- Correction factors for ionization chambers
- Calculation of dose kernels
- Patient dose calculation
- Estimation of photoneutron/electron contamination/nuclear fragmentation
- Imaging (x-ray, CT, PET, prompt-gamma)
- Radiobiology, RBE modeling

Reference Literature


BELONGS TO A.E. NAHUM

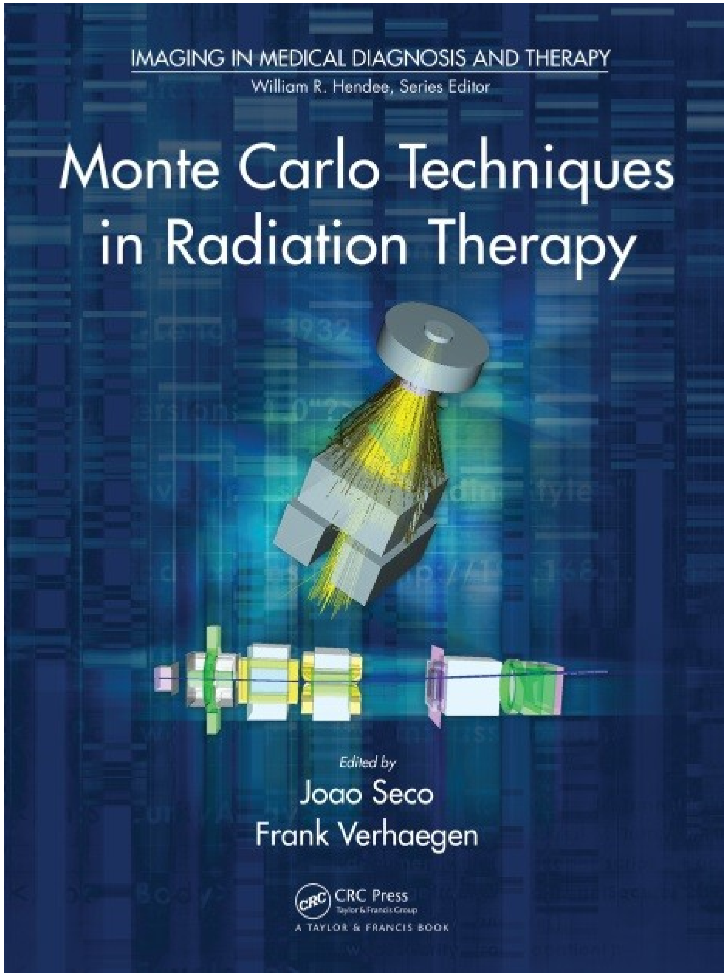
Monte Carlo Transport of Electrons and Photons

Edited by Theodore M. Jenkins, Walter R. Nelson, and Alessandro Rindi

ETTORE MAJORANA INTERNATIONAL SCIENCE SERIES
Series Editor: Antonino Zichichi

PHYSICAL SCIENCES

1986


IMAGING IN MEDICAL DIAGNOSIS AND THERAPY
William R. Hendee, Series Editor

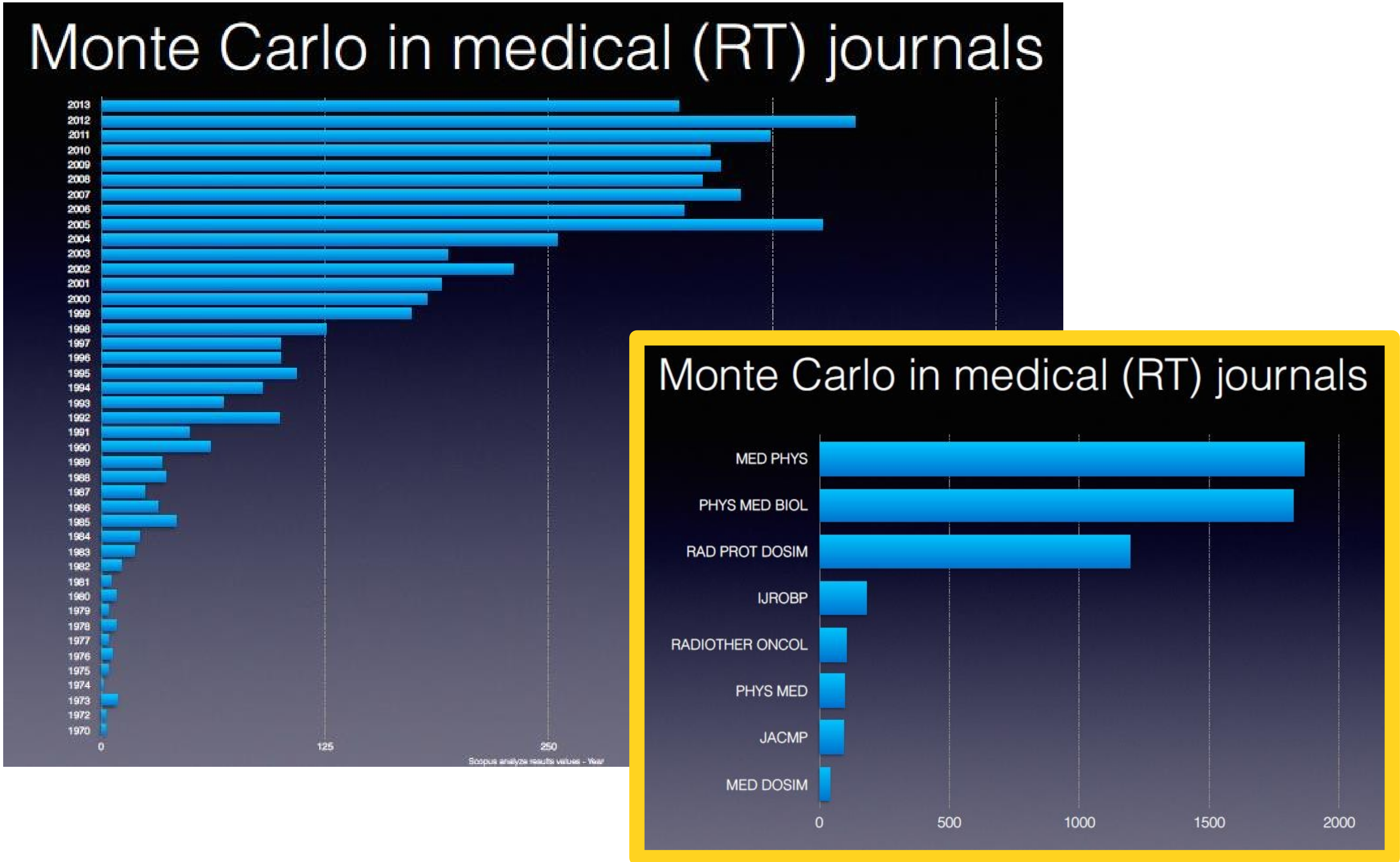
Monte Carlo Techniques in Radiation Therapy

Edited by
Joao Seco
Frank Verhaegen

CRC Press
Taylor & Francis Group
A TAYLOR & FRANCIS BOOK

2014

Monte Carlo Method in Medical Physics

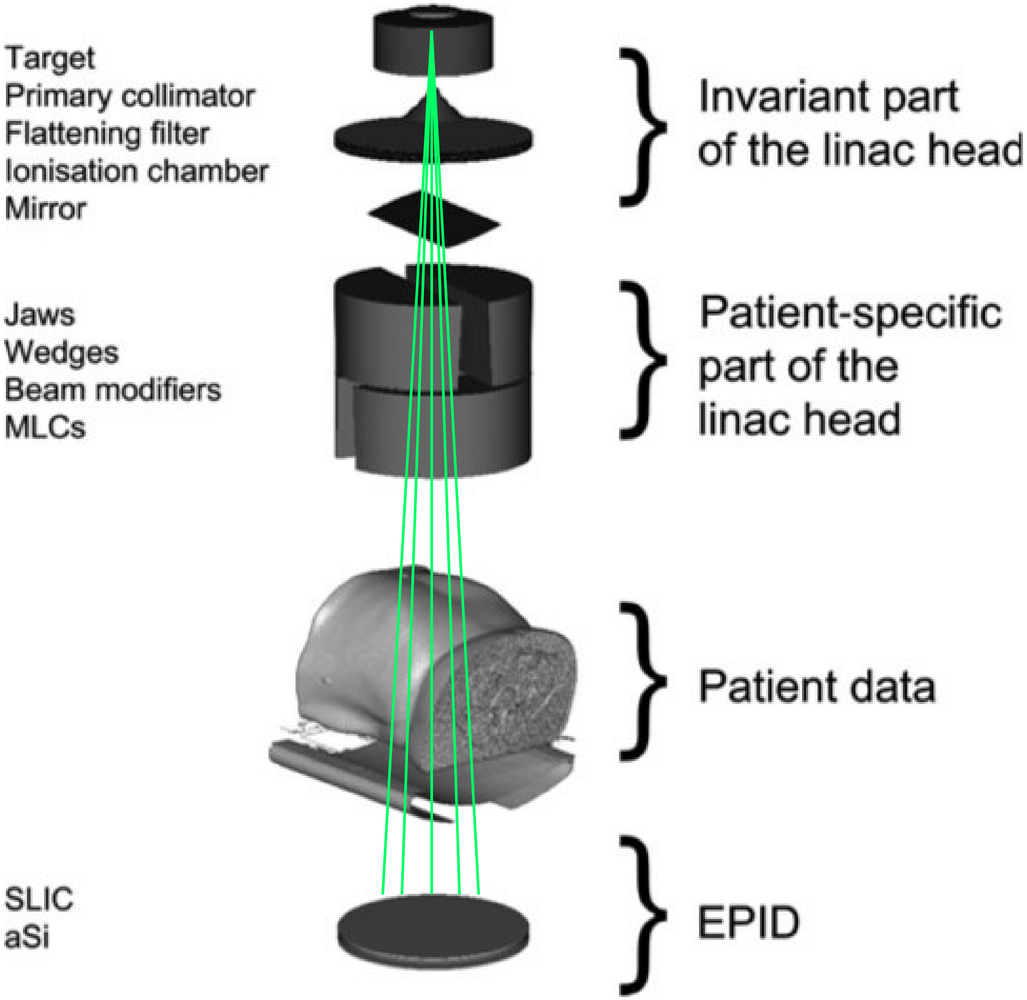


By courtesy of Emiliano Spezi

Monte Carlo for accurate dose calculation

Radiotherapy and the Problem of Dose Calculation

Radiotherapy requires accurate and precise dose calculation to patients.



Spezi and Lewis RPD (2008) 131 123

Radiation Transport Through Matter

The accurate transport of radiation through matter is described by the **Linear Boltzmann Transport Equation:**

$$\left[\frac{\partial}{\partial s} + \frac{p}{|p|} \cdot \frac{\partial}{\partial x} + \mu(x,p)\right] \psi(x,p,s) = \int \mathrm{d}x' \int \mathrm{d}p' \, \mu(x,p,p')\psi(x',p',s)$$

But

- there is **no general solution in closed form.**

- analytical solutions are possible for only very simple and highly idealized situations.

Solution techniques:

- analytical approximations

- implicit Monte Carlo simulation

Analytical solution

Very fast but **limited accuracy**

VS

Monte Carlo solution

Slow but **simple** and **accurate**

Past: 1970s

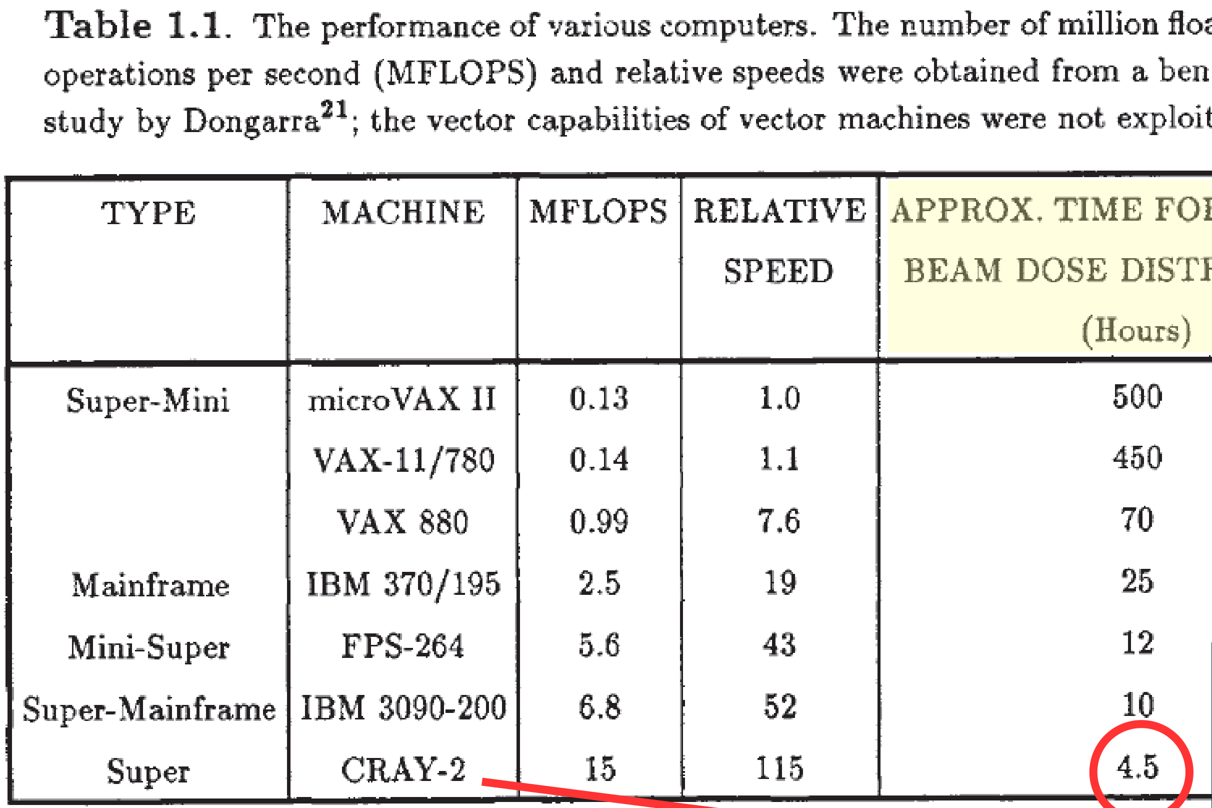
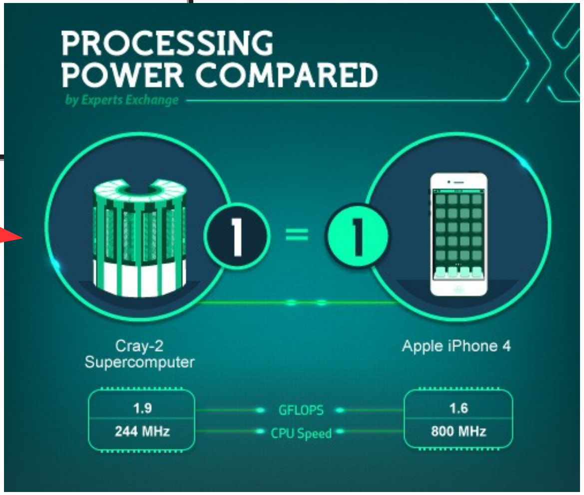


Table 1.1. The performance of various computers. The number of million floating point operations per second (MFLOPS) and relative speeds were obtained from a benchmarking study by Dongarra[21]; the vector capabilities of vector machines were not exploited.

TYPE	MACHINE	MFLOPS	RELATIVE SPEED	APPROX. TIME FOR PHOTON BEAM DOSE DISTRIBUTION (Hours)
Super-Mini	microVAX II	0.13	1.0	500
	VAX-11/780	0.14	1.1	450
	VAX 880	0.99	7.6	70
Mainframe	IBM 370/195	2.5	19	25
Mini-Super	FPS-264	5.6	43	12
Super-Mainframe	IBM 3090-200	6.8	52	10
Super	CRAY-2	15	115	4.5



Monte Carlo dose calculation could not be performed for patient treatments back then!

Analytical models had to be used.

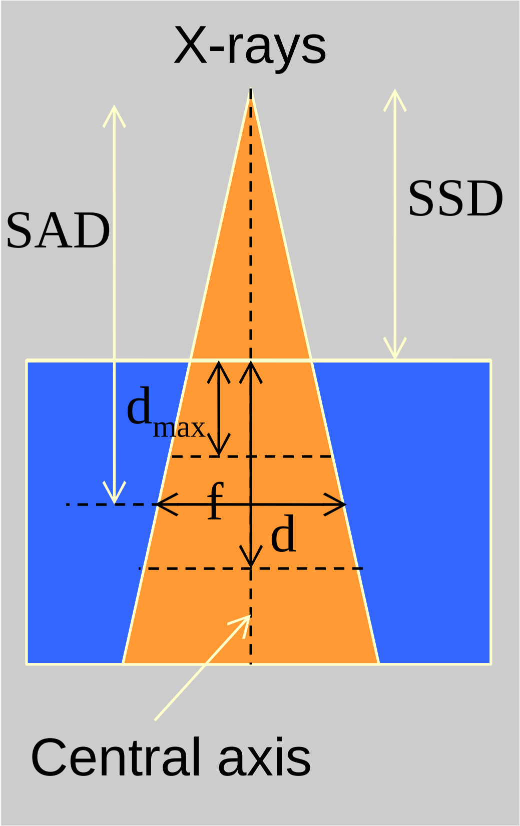
Standard Dose Calculation in Clinical Treatment Planning Systems

PAST: 1970s until mid 1990s
Correction-based or Experiment-based Algorithms
TAR, TMR or TPR methods

Depth-Dose for Photon Beams

The photon beam is attenuated when traversing the patient and the absorbed dose in the medium varies with depth.

The variation depends on the beam geometry, quality, and the medium composition.

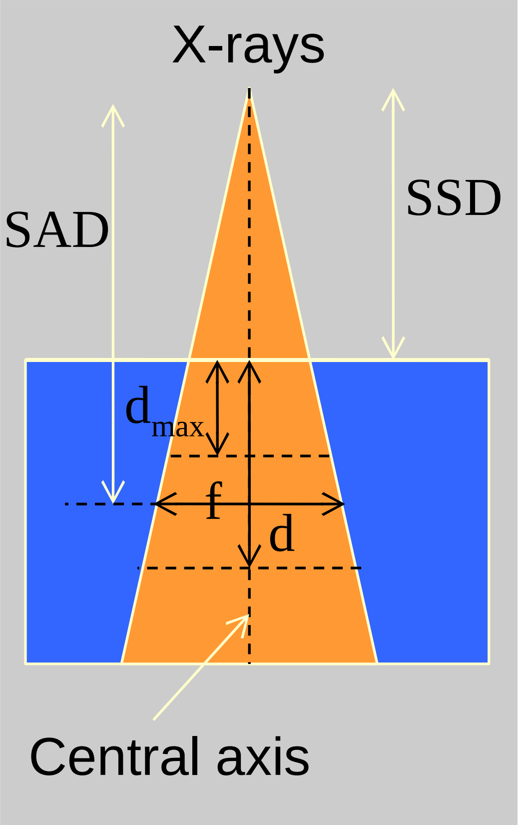


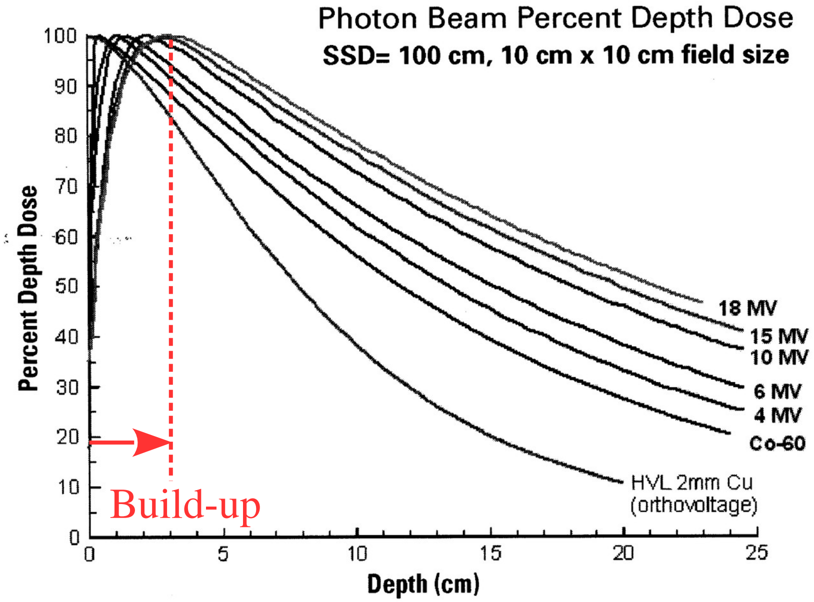
SAD: Source-Axis-Distance
SSD: Source-Surface-Distance

Depth-Dose for Photon Beams

The photon beam is attenuated when traversing the patient and the absorbed dose in the medium varies with depth.

The variation depends on the beam geometry, quality, and the medium composition.





Energy	d_{max}
^{60}Co	0.5 cm
6 MV	1.5 cm
18 MV	3.3 cm

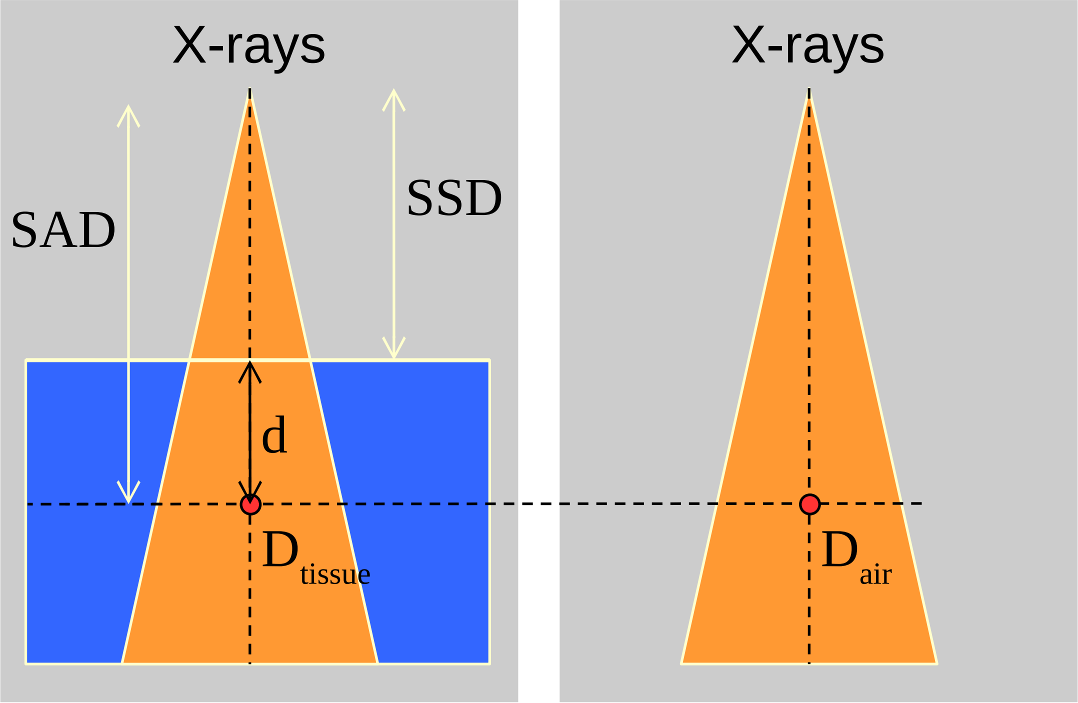
$$PDD(d,f,SSD)=\frac{D(SSD+d,f)}{D(SSD+d_{max},f)}\times 100\%$$

SAD: Source-Axis-Distance
SSD: Source-Surface-Distance

Past: 1970s

Phenomenological dose calculation – TAR

Method based on the parameterisation of the dose distribution using measured data sets in water phantom and in air (so-called dosimetric base data).



Tissue Air Ratio (TAR)

$$\boxed{TAR = D_{tissue}/D_{air}}$$

The TAR is affected by the field size and beam energy as well as the depth in the phantom.

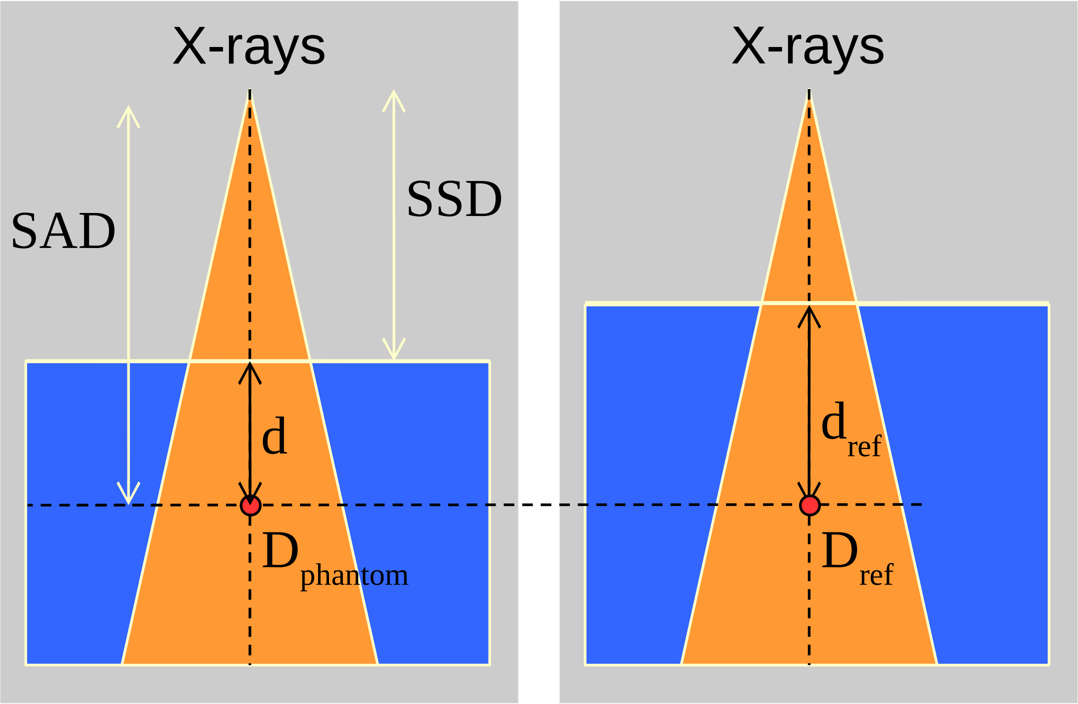
Does not account for the build-up in the air measurement.

Not appropriate for modern high energy photons beams.

Past: 1970s

Phenomenological dose calculation – TPR and TMR

The TPR is a variation of the TAR that makes it suitable for use at high energy photon beams. It allows correction of MUs to account for changes in dose at depths other than the reference.



Tissue Phantom Ratio (TPR)

$$\boxed{TPR = D_{phantom}/D_{ref}}$$

Fixed reference depth d_{ref} usually 5 cm. Accounts for the build-up of dose in water.

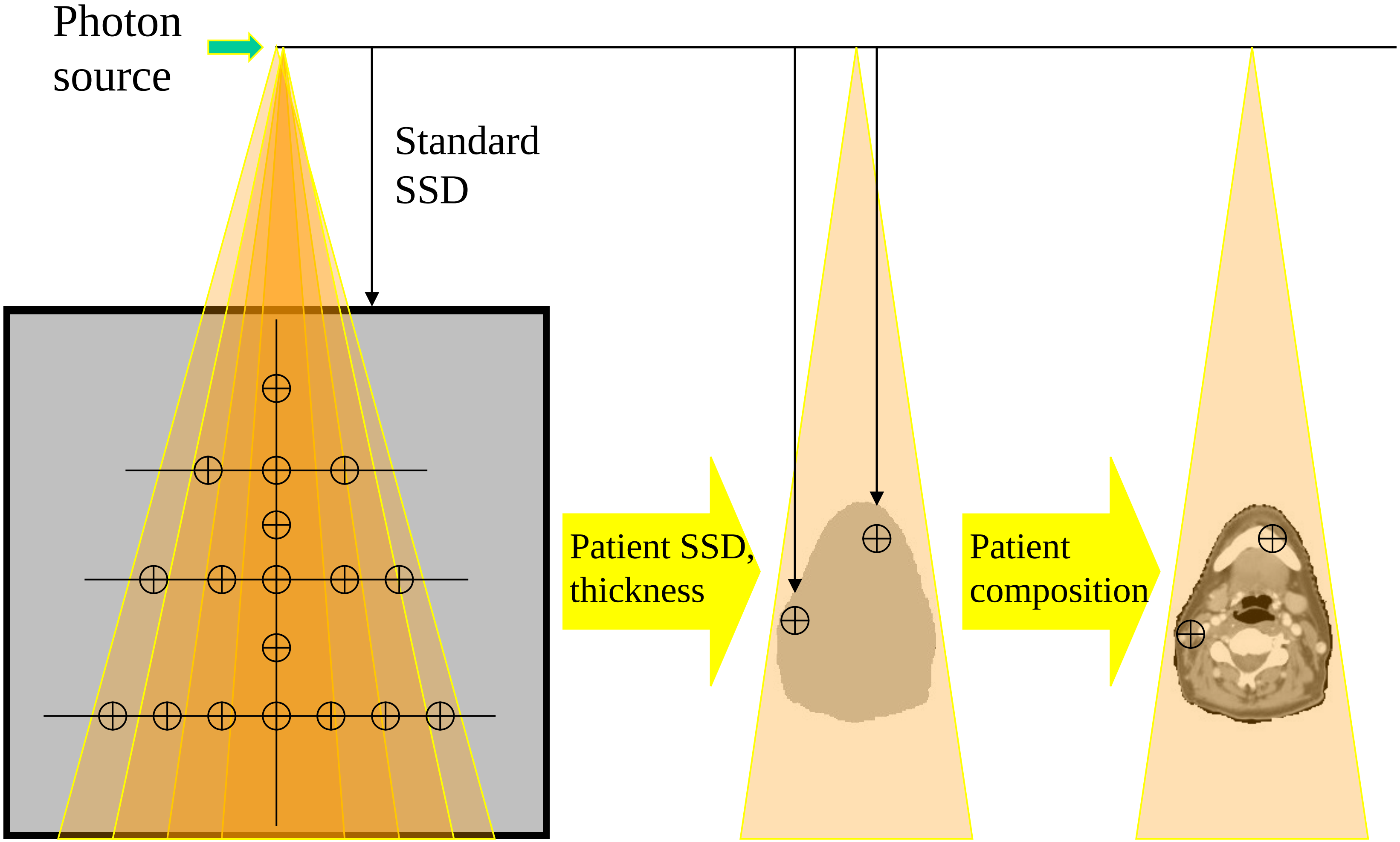
Tissue Maximum Ratio (TMR)

Similar to TPR, but d_{ref} is taken as the depth of maximum dose.

Past: 1970s

Limitation: Does not handle electronic disequilibrium

Correction-based Algorithms



Photon source

Standard SSD

Patient SSD, thickness

Patient composition

Measurements

Calculations (correction factors)

Standard Dose Calculation in Clinical Treatment Planning Systems

PAST: 1970s until mid 1990s
Correction-based or Experiment-based Algorithms
TAR, TMR or TPR methods

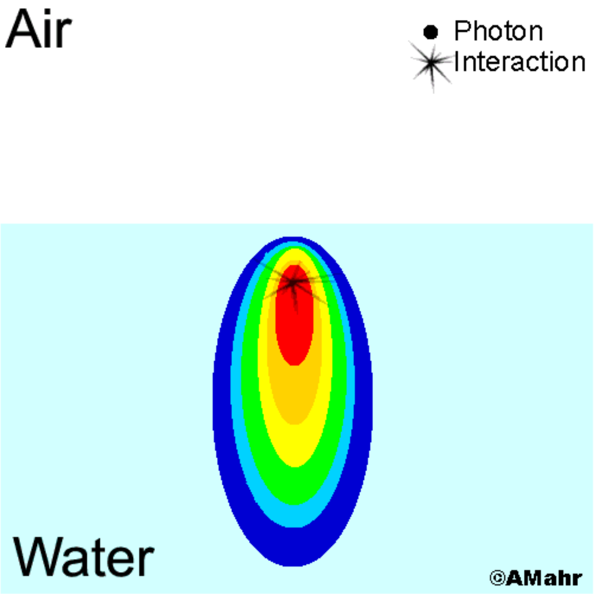
PRESENT: mid 1990s until 2010-15
Model-based or Superposition/Convolution-based Algorithms

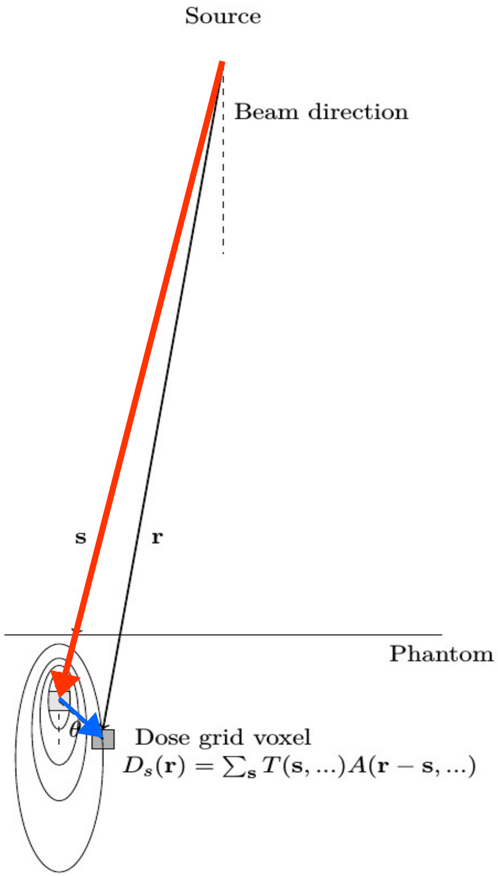
Present: mid 1990s until 2010-15

Convolution methods: Kernels and pencil beams

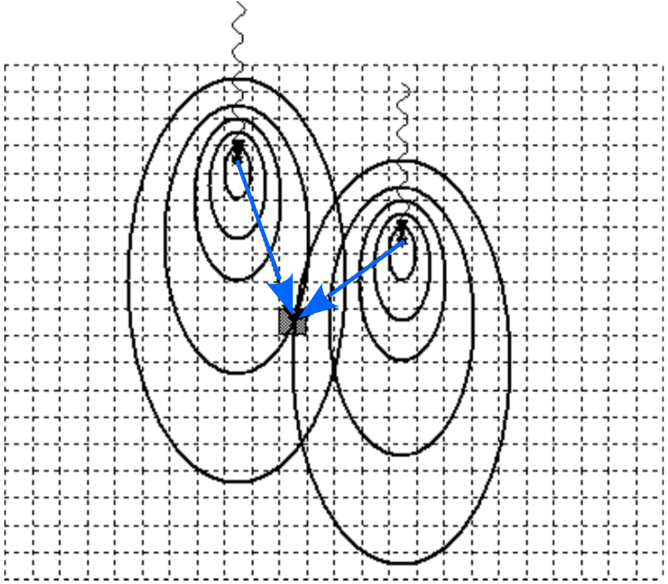
Method based on calculating microscopic particle interactions of the energy deposition in water for a defined “elementary-photon-beam”.

Point Kernel (calculated with Monte Carlo)





Dose Contribution from Multiple Kernels



Present: mid 1990s until 2010-15

Convolution methods: Kernels and pencil beams

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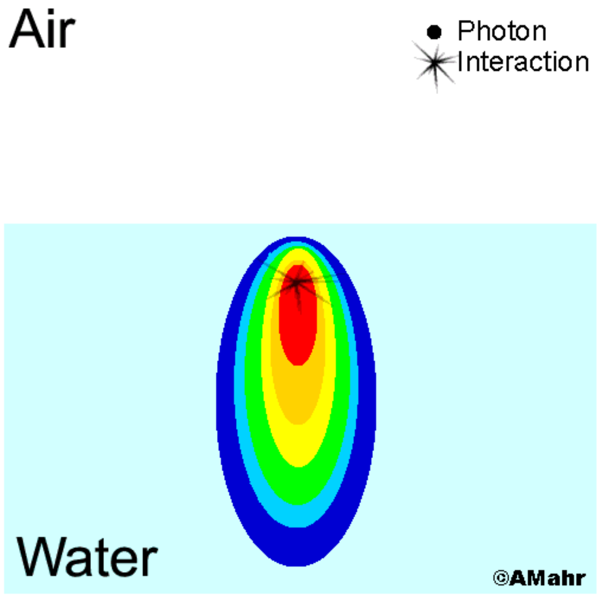
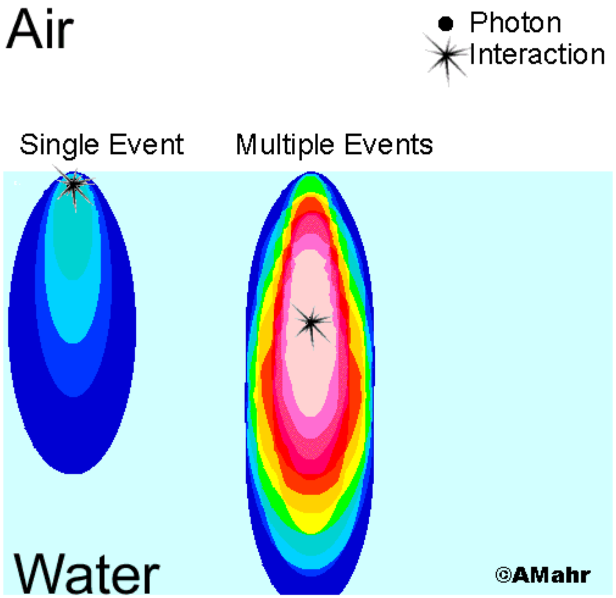
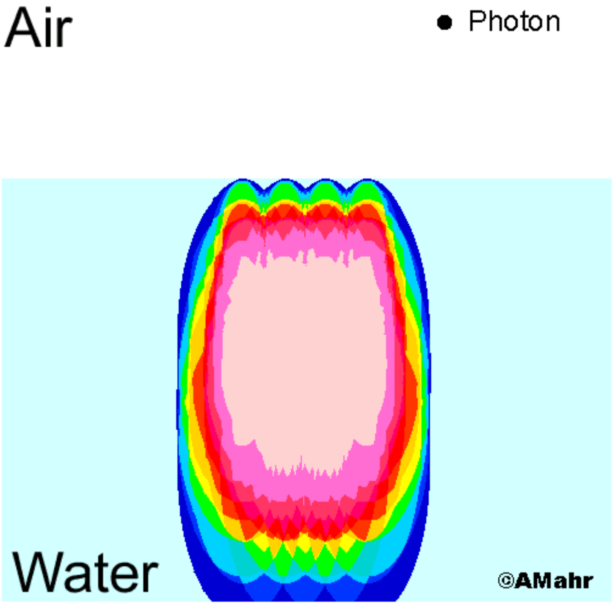


Multiple Point Kernel

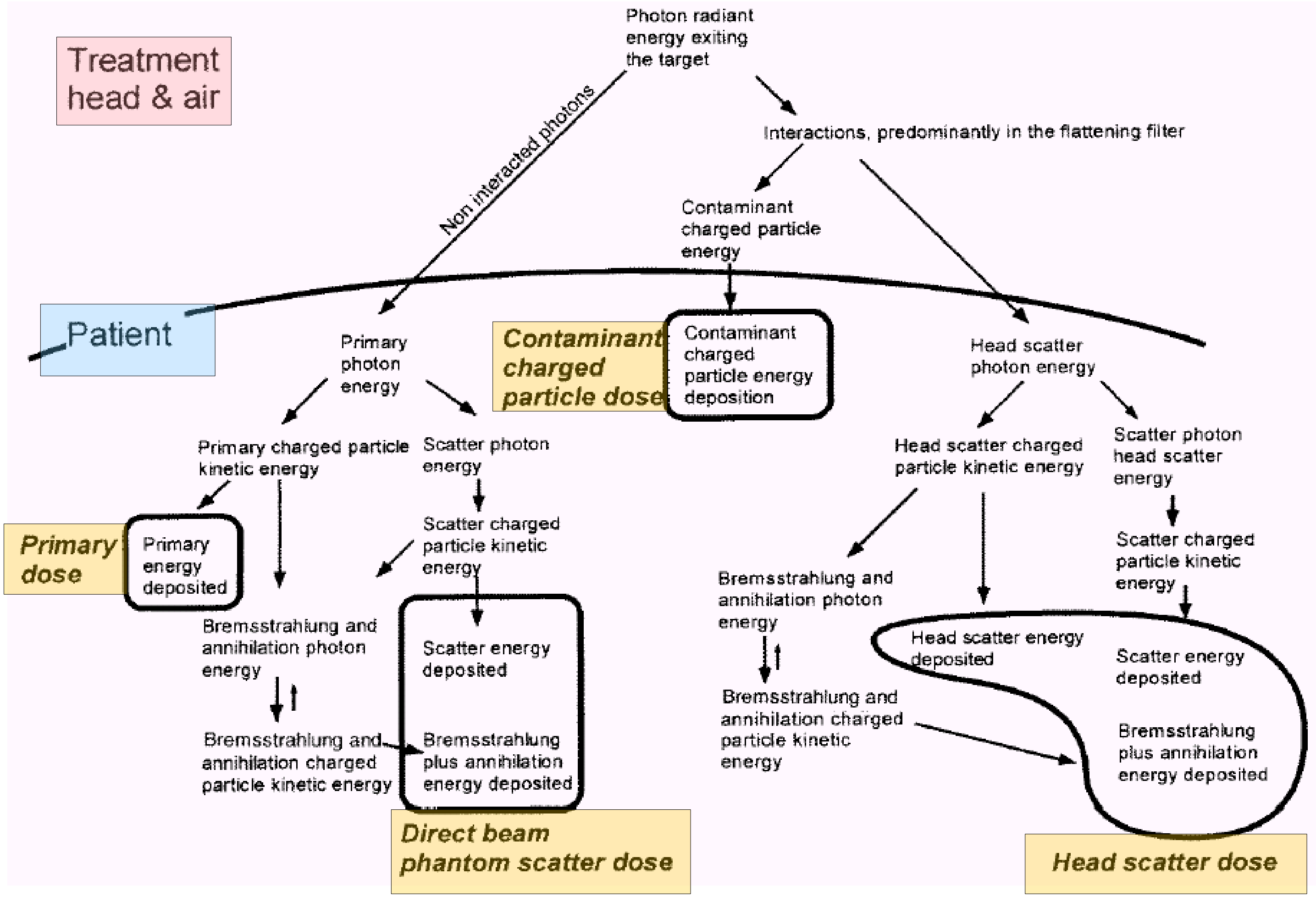


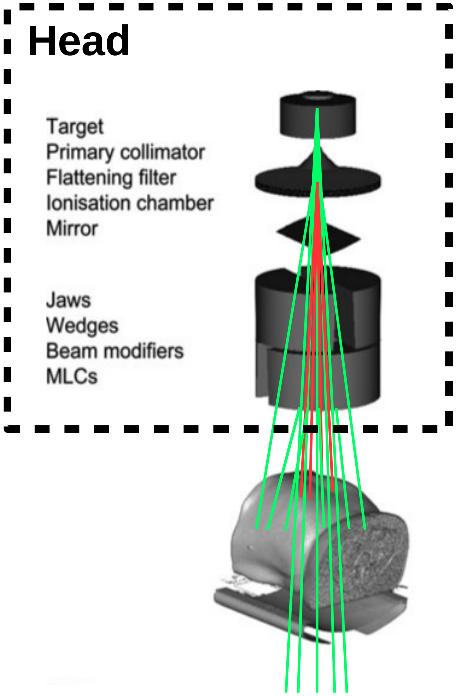
Pencils Kernel



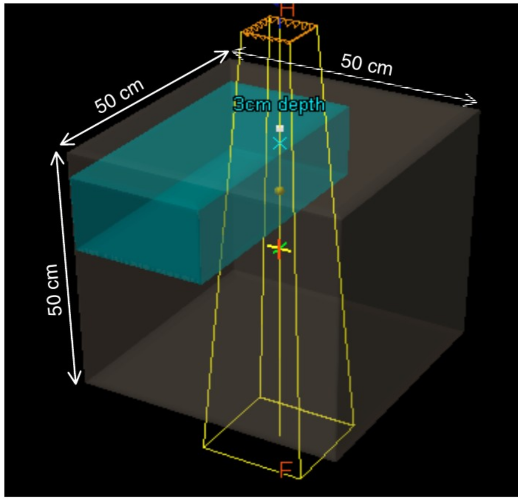
Present: mid 1990s until 2010-15

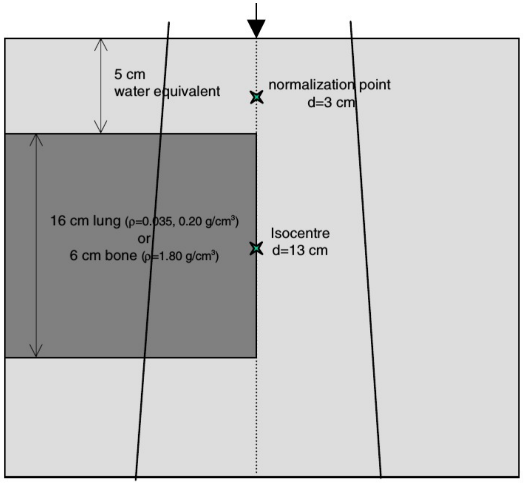
Analytical models compute the dose in the patient by contribution of several components: **primary dose**, direct beam **phantom scatter** dose, **contaminant** charged particle dose and **head scatter** dose.

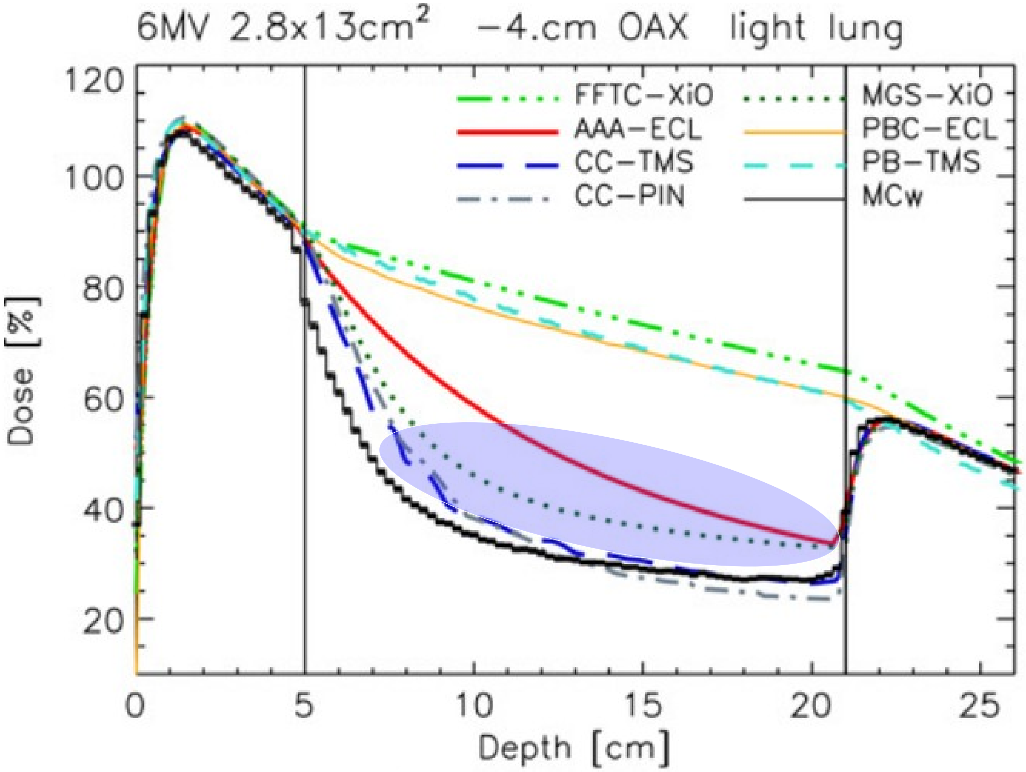




The Problem of Interfaces





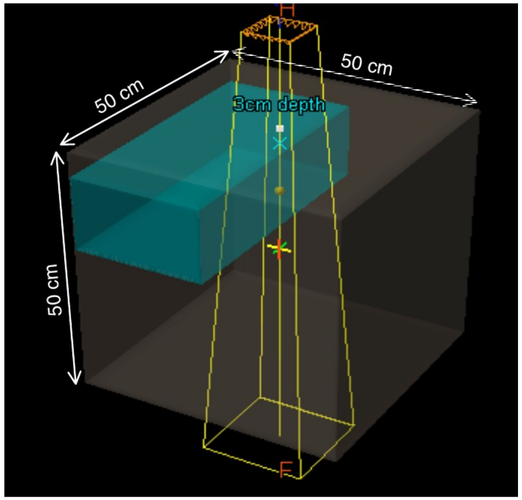


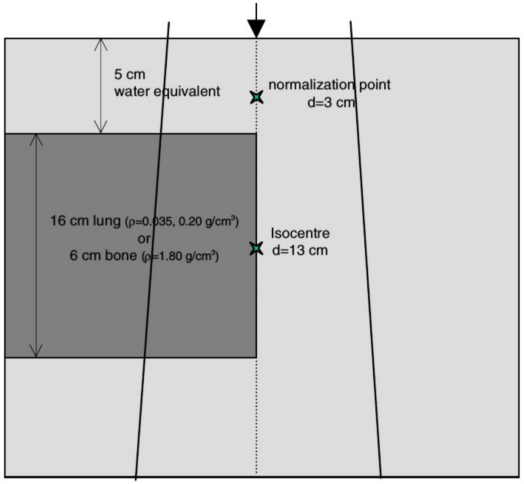
PBC, PB, FFTC models: based on equivalent path length (electron transport not separately modeled)

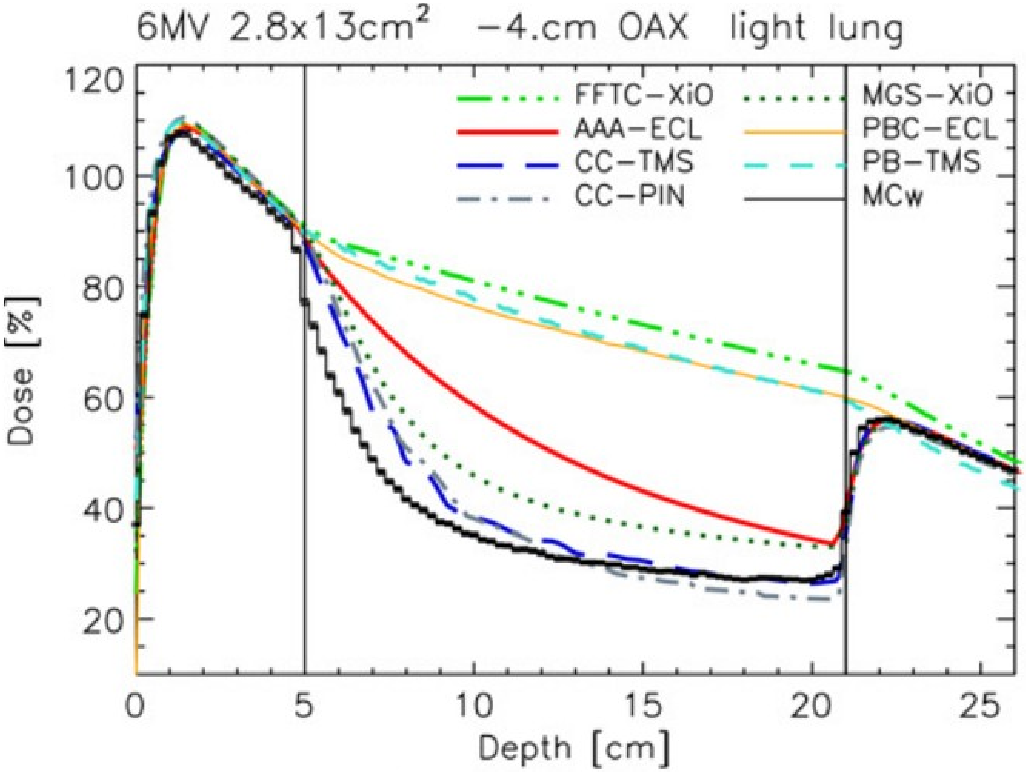
AAA and CC algorithms: approximate electron and photon transport

Fogliatat et al *Phys Med Biol* (2007) **52** 1363

The Problem of Interfaces



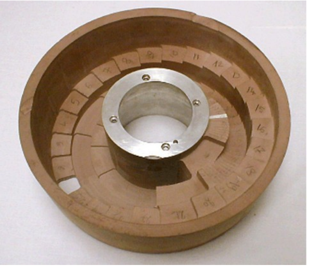


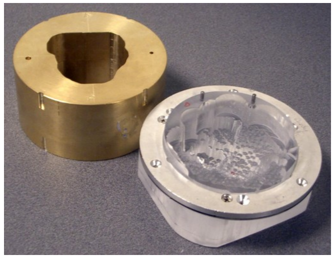


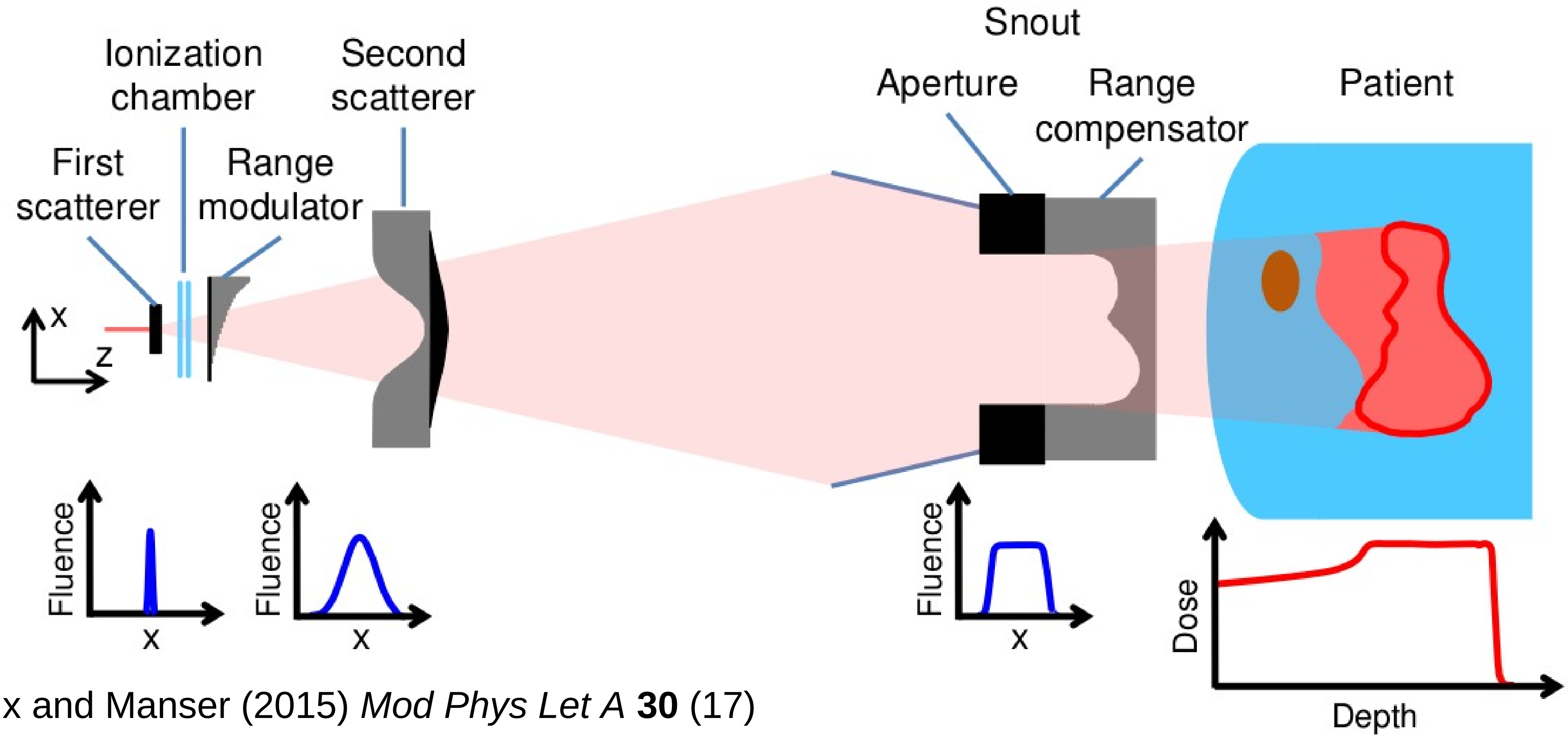
Superposition models can handle electronic disequilibrium
But, limitation regarding material interface (different stopping power/scattering)

Fogliatat et al *Phys Med Biol* (2007) **52** 1363

Proton/Ion beam delivery: Passive scattering

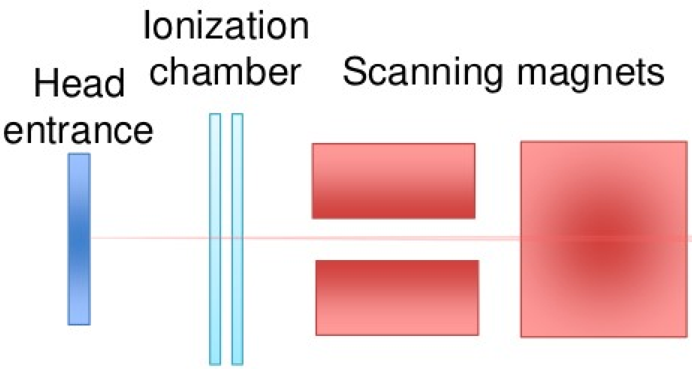


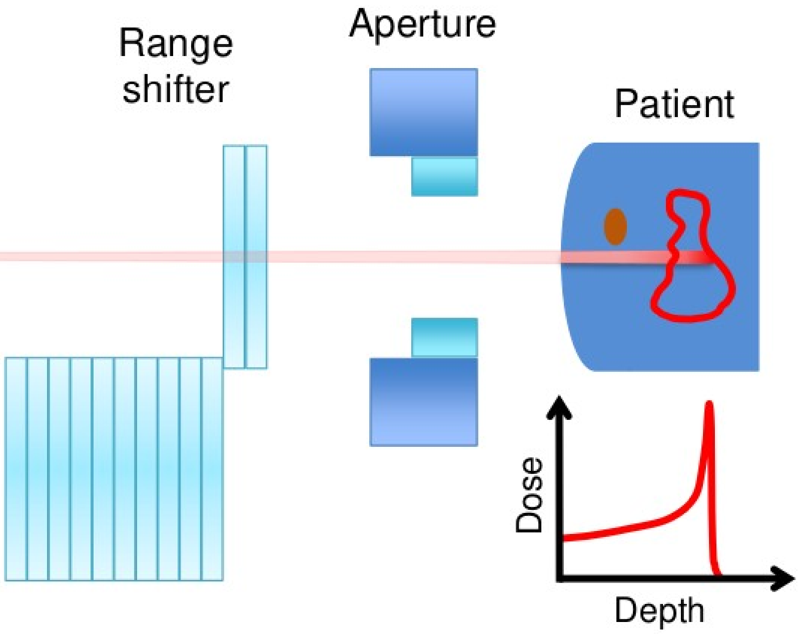




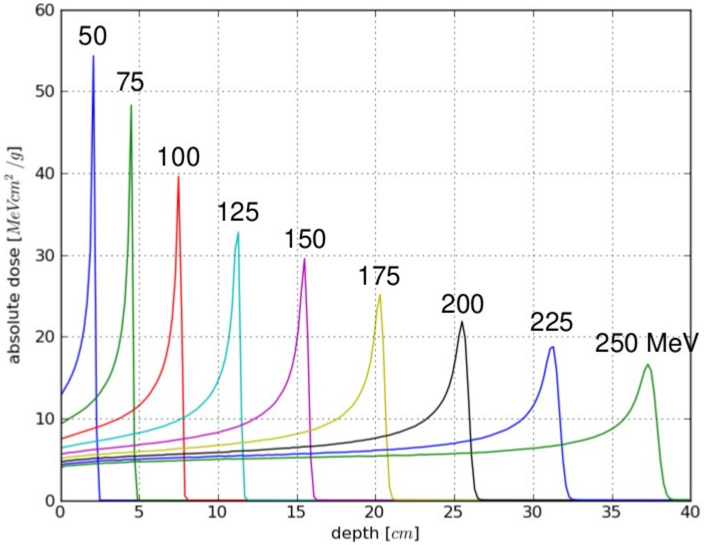
Fix and Manser (2015) *Mod Phys Let A* **30** (17)

Proton/Ion beam delivery: Pencil beam/spot scanning



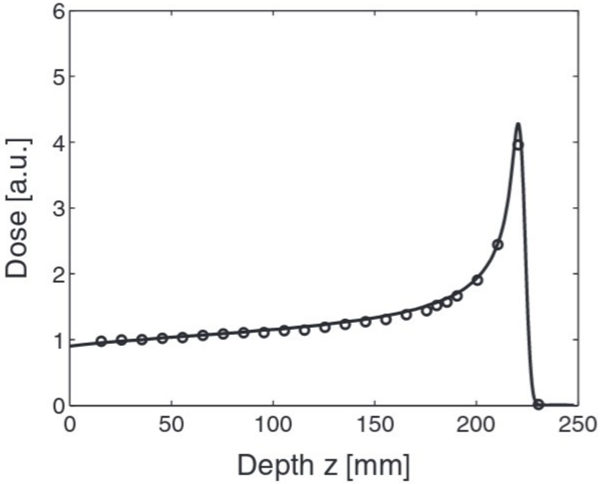


Fix and Manser (2015) *Mod Phys Let A* **30** (17)

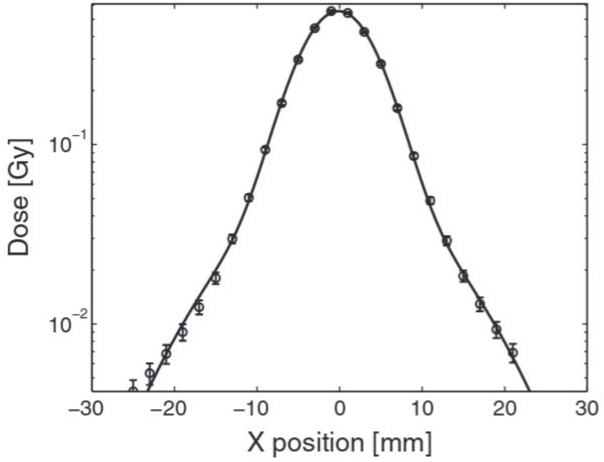


Analytical Algorithms for Dose Calculation of Ion Beams

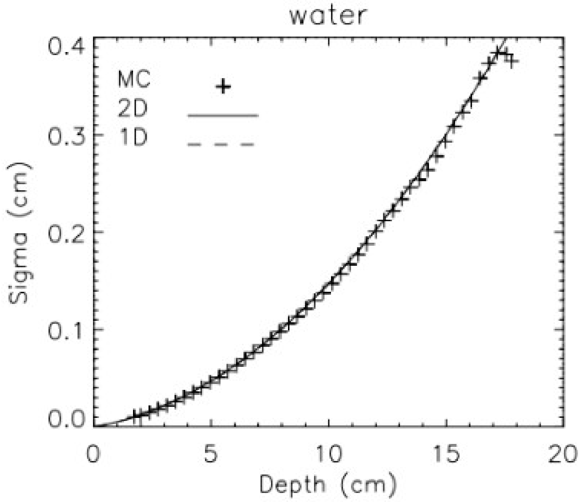
Depth-dose profile $Z(z,E_0)$

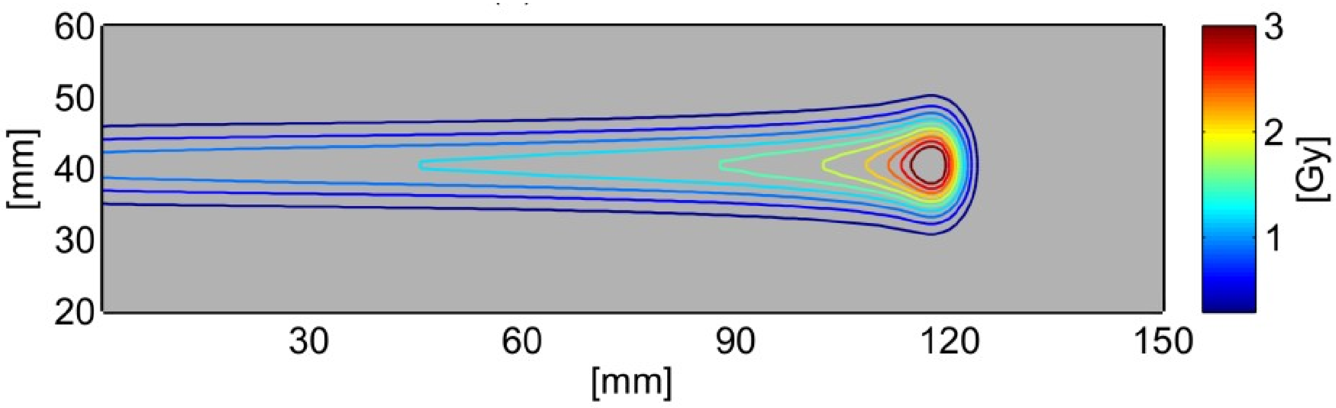


Radial-dose profile $L(z,E_0,r)$



Scattering in medium



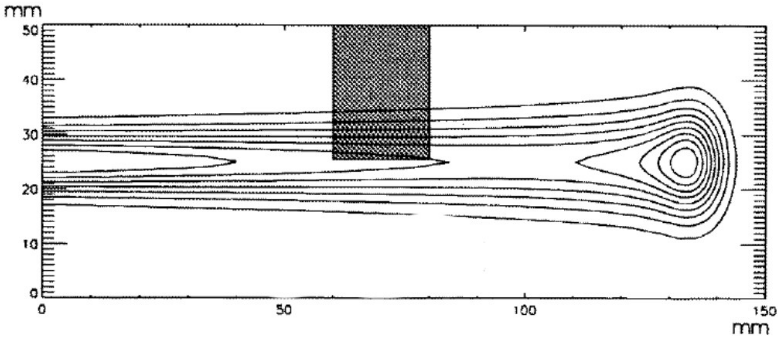


TPS for ion beams are mostly based on pencil beam algorithms

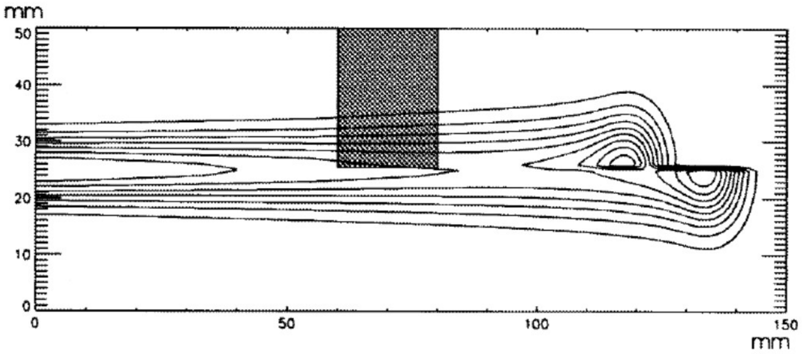
$$d = L(z, E_0, r) \cdot Z(z, E_0)$$

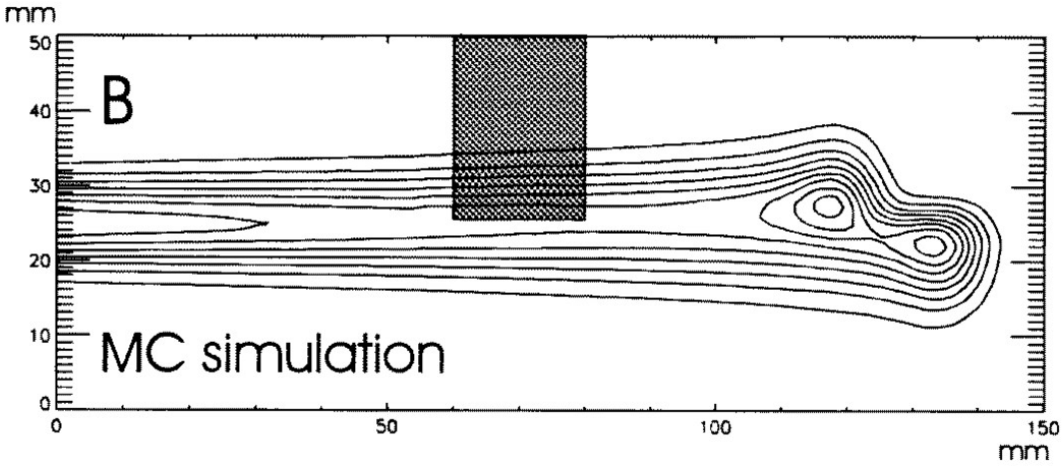
The Problem of Tissue Inhomogeneity

Central axis ray tracing



Point of interest ray tracing





Schaffner et al *Phys Med Biol* (1998) **44**

Standard Dose Calculation in Clinical Treatment Planning Systems

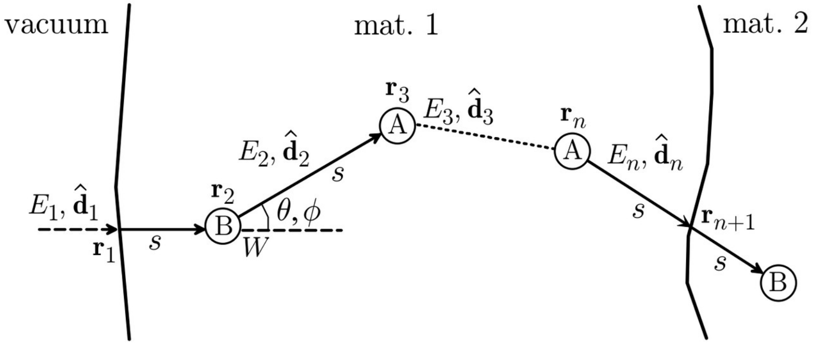
PAST: 1970s until mid 1990s
Correction-based or Experiment-based Algorithms
TAR, TMR or TPR methods

PRESENT: mid 1990s until 2010-15
Model-based or Superposition/Convolution-based Algorithms

FUTURE: from ~2015 onwards
Stochastic-based or Monte Carlo-based Algorithms

(Review) Monte Carlo Particle Transport Simulation in a Nutshell

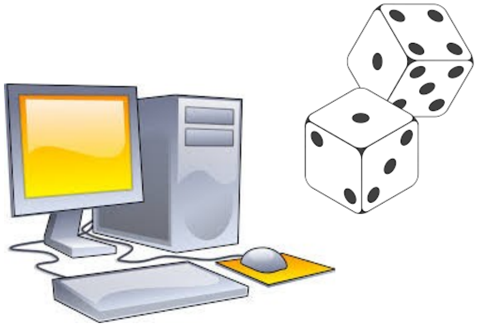
Particles are transported **step-by-step** accounting for the stochastic nature of their microscopic interactions.



❶ The **distance to the next step** is sampled from the total cross section.

❷ The type of interaction is sampled and the scattering event modeled.

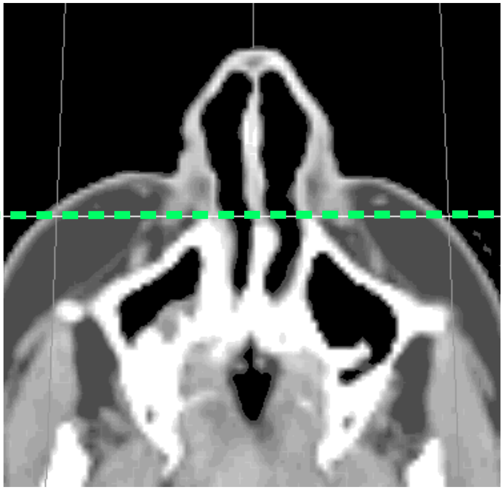
❸ The transport continues with the next step/ or secondary particles.

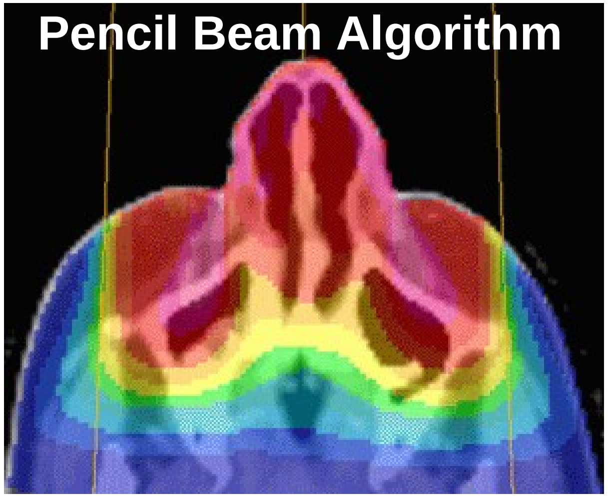


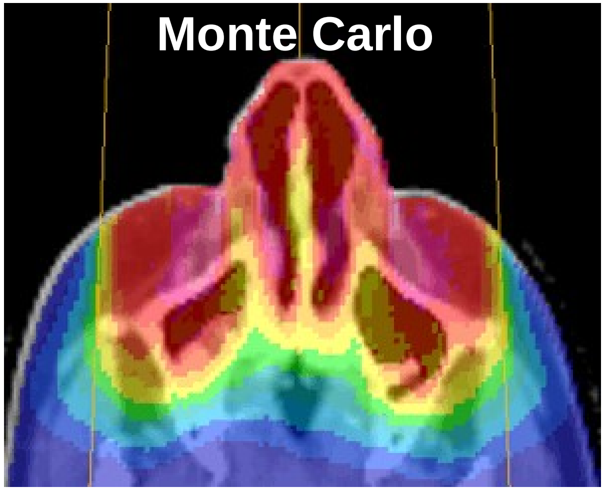
Monte Carlo can easily handle interfaces of different materials and complex geometries → Scattering and non-equilibrium is accounted for

Analytical vs Monte Carlo Dose Calculation (Photons)

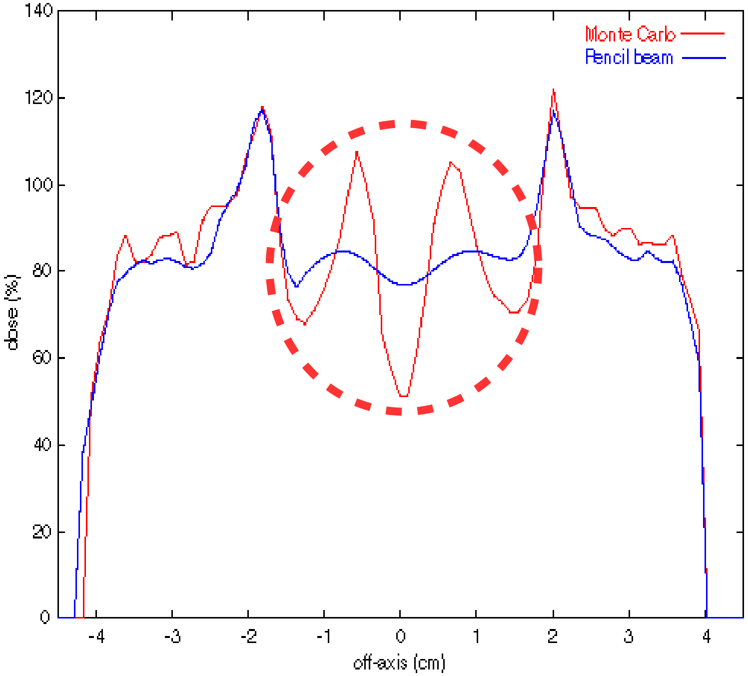
Irradiation of highly heterogeneous geometry.



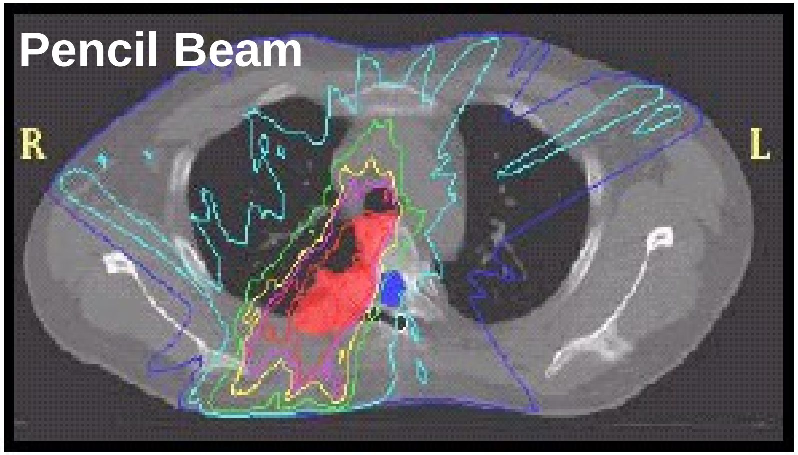


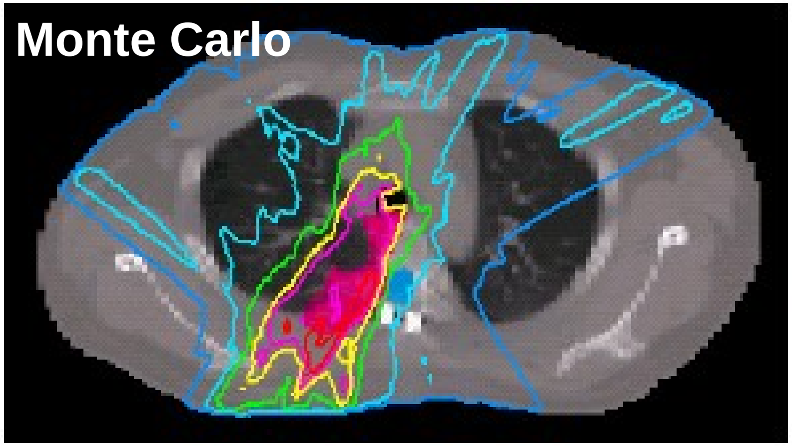


Pencil beam algorithm fails to predicts dose inhomogeneity.

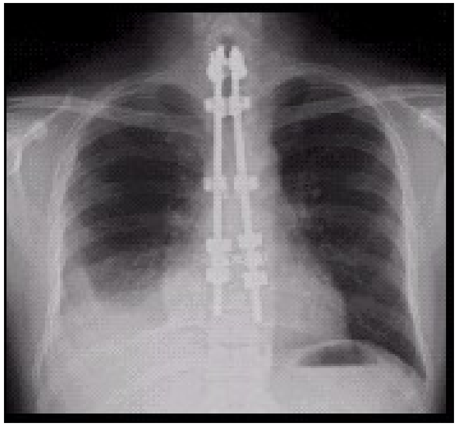


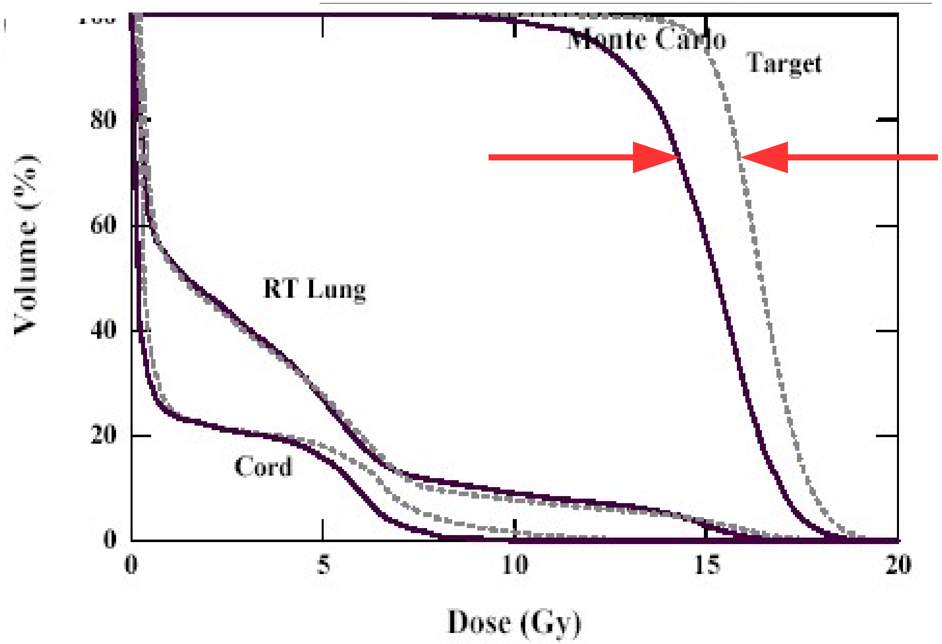
Analytical vs Monte Carlo Dose Calculation (Photons)





Pencil Beam

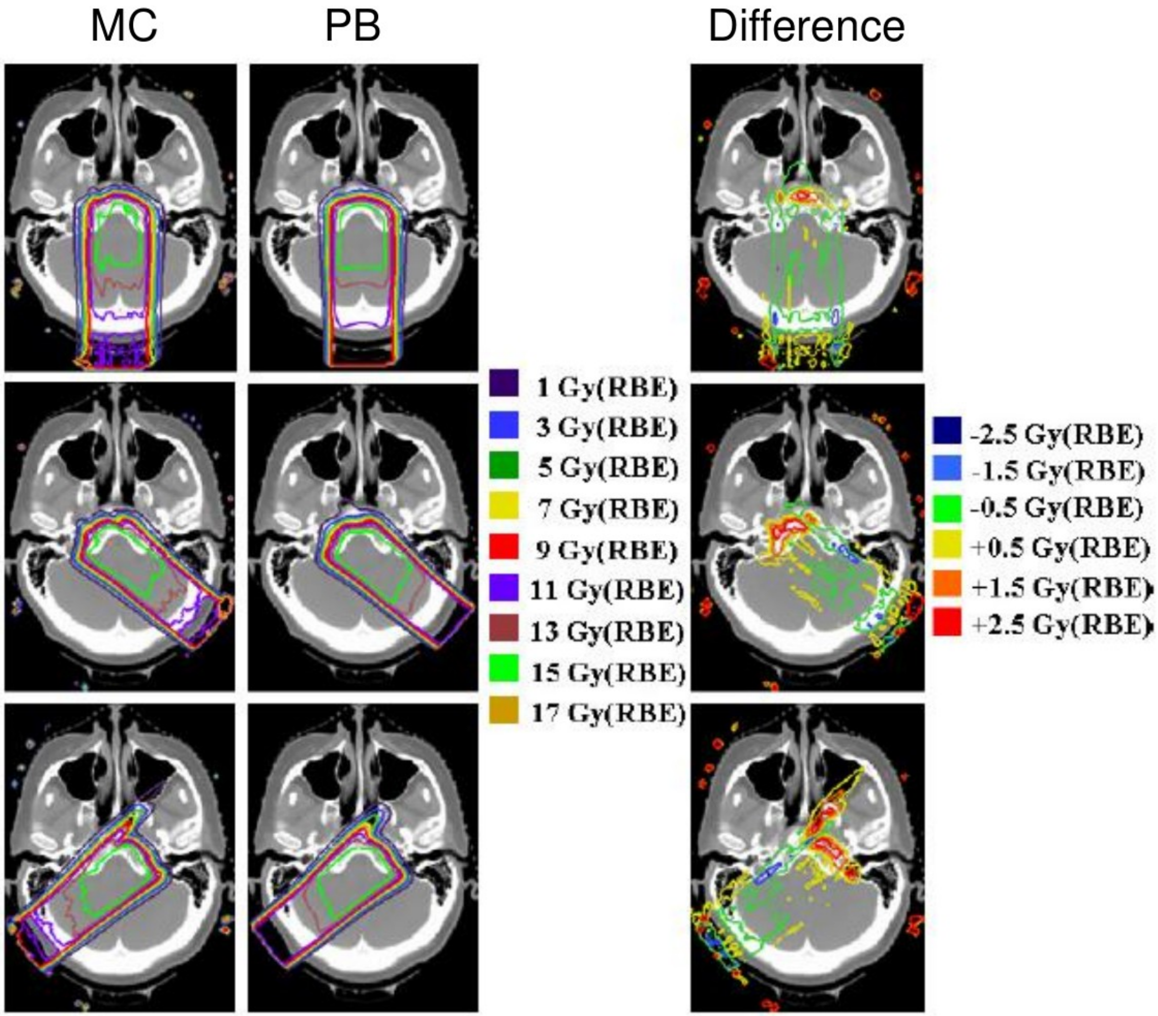




By courtesy of João Seco

Analytical vs Monte Carlo Dose Calculation (Protons)

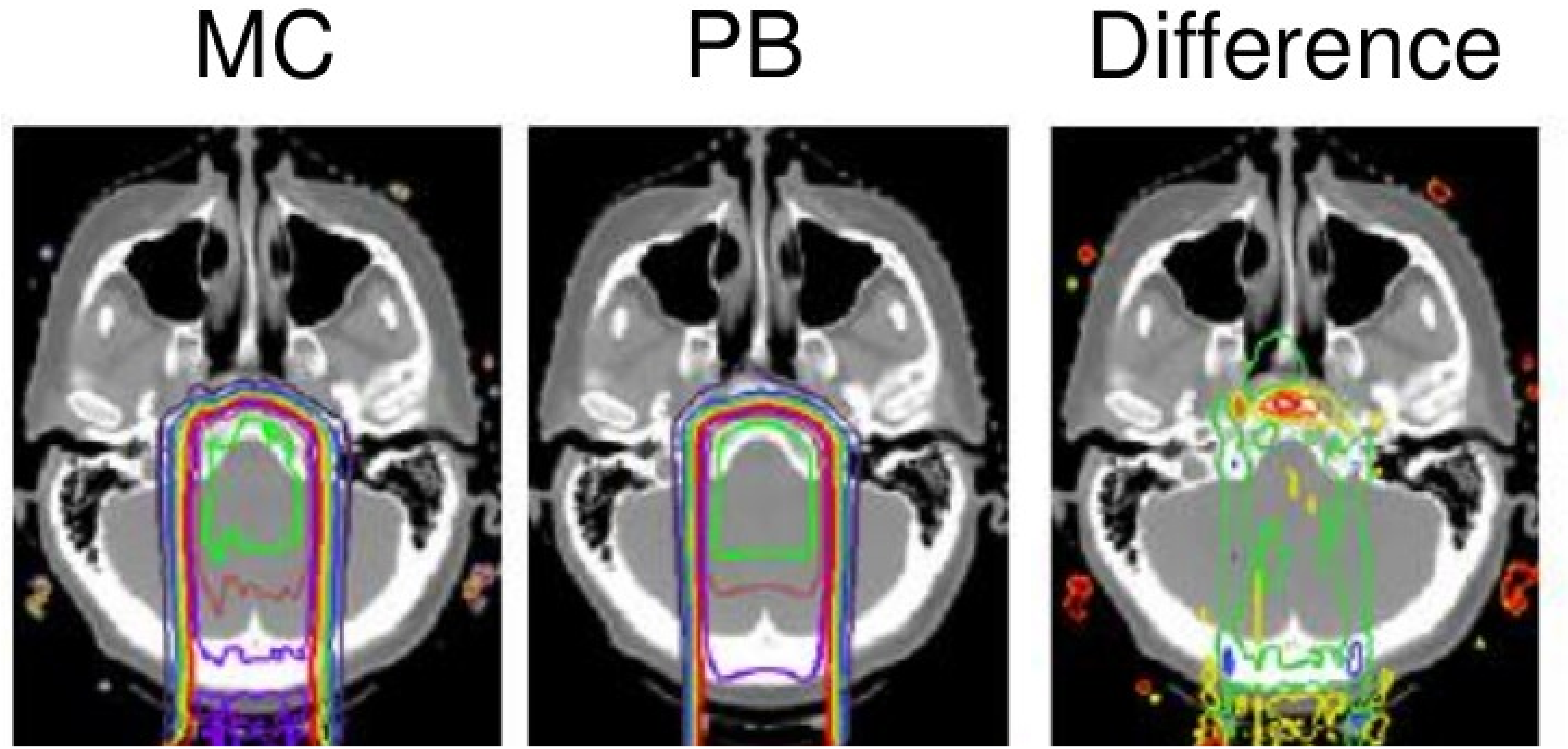
Para-spinal tumor



Paganetti et al., PMB 53 (17) 2008

Analytical vs Monte Carlo Dose Calculation (Protons)

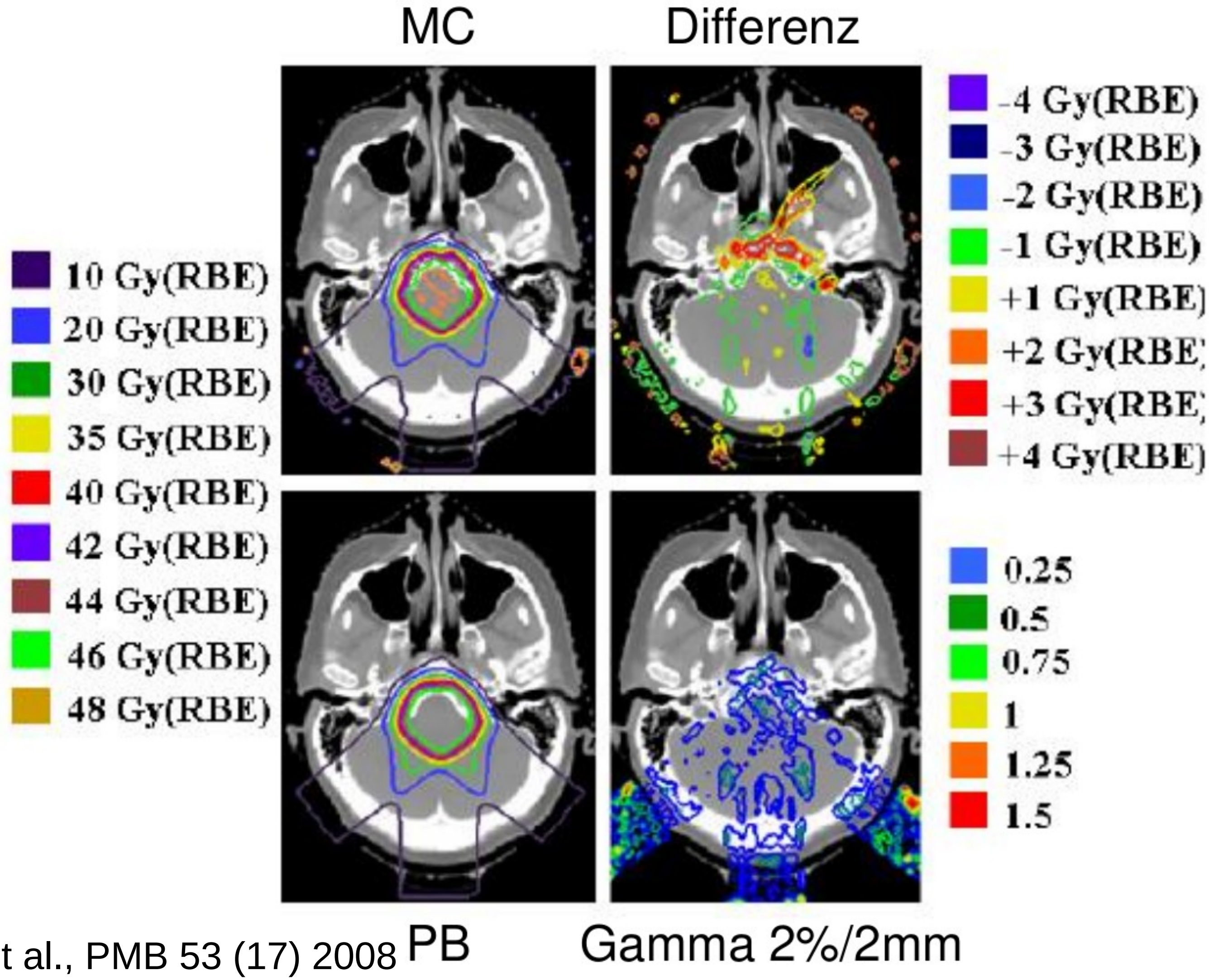
Para-spinal tumor



Paganetti et al., PMB 53 (17) 2008

Analytical vs Monte Carlo Dose Calculation (Protons)

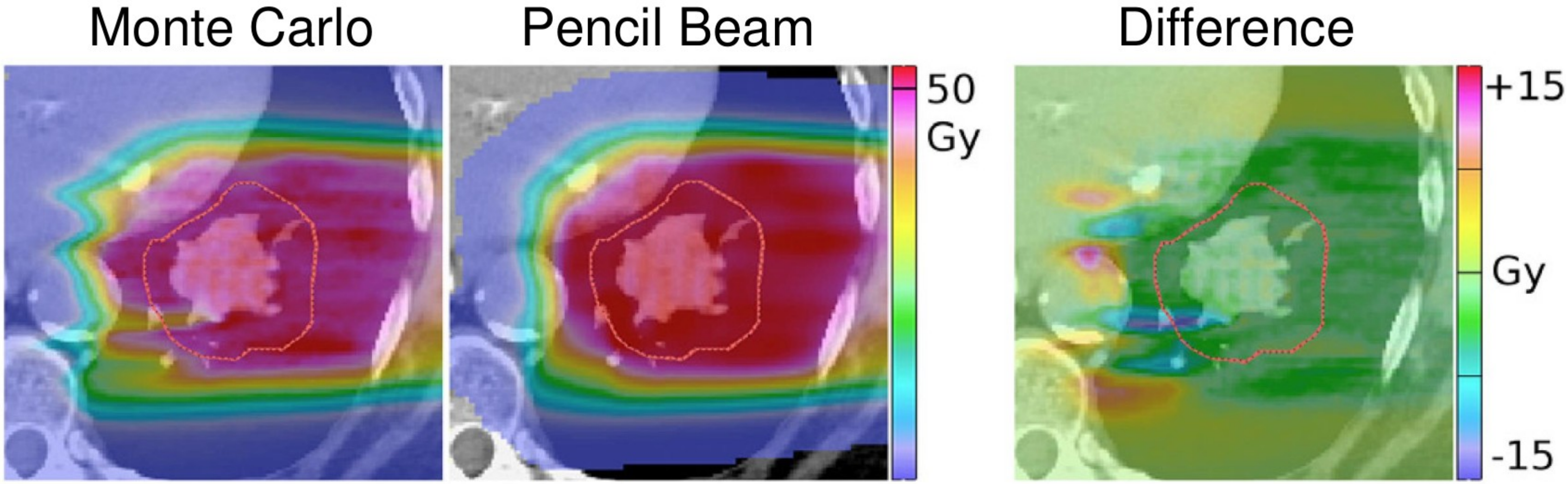
Para-spinal tumor, total treatment plan



Paganetti et al., PMB 53 (17) 2008

Analytical vs Monte Carlo Dose Calculation (Protons)

Lung case

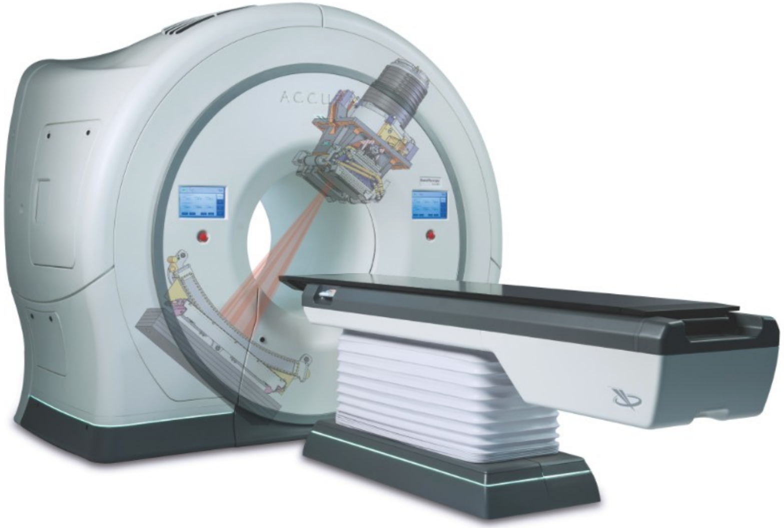


Grassberger et al., PMB 60 (17) 2015

Monte Carlo for modeling of treatment devices

Radiotherapy Treatment Devices: Photon and Electron Beams

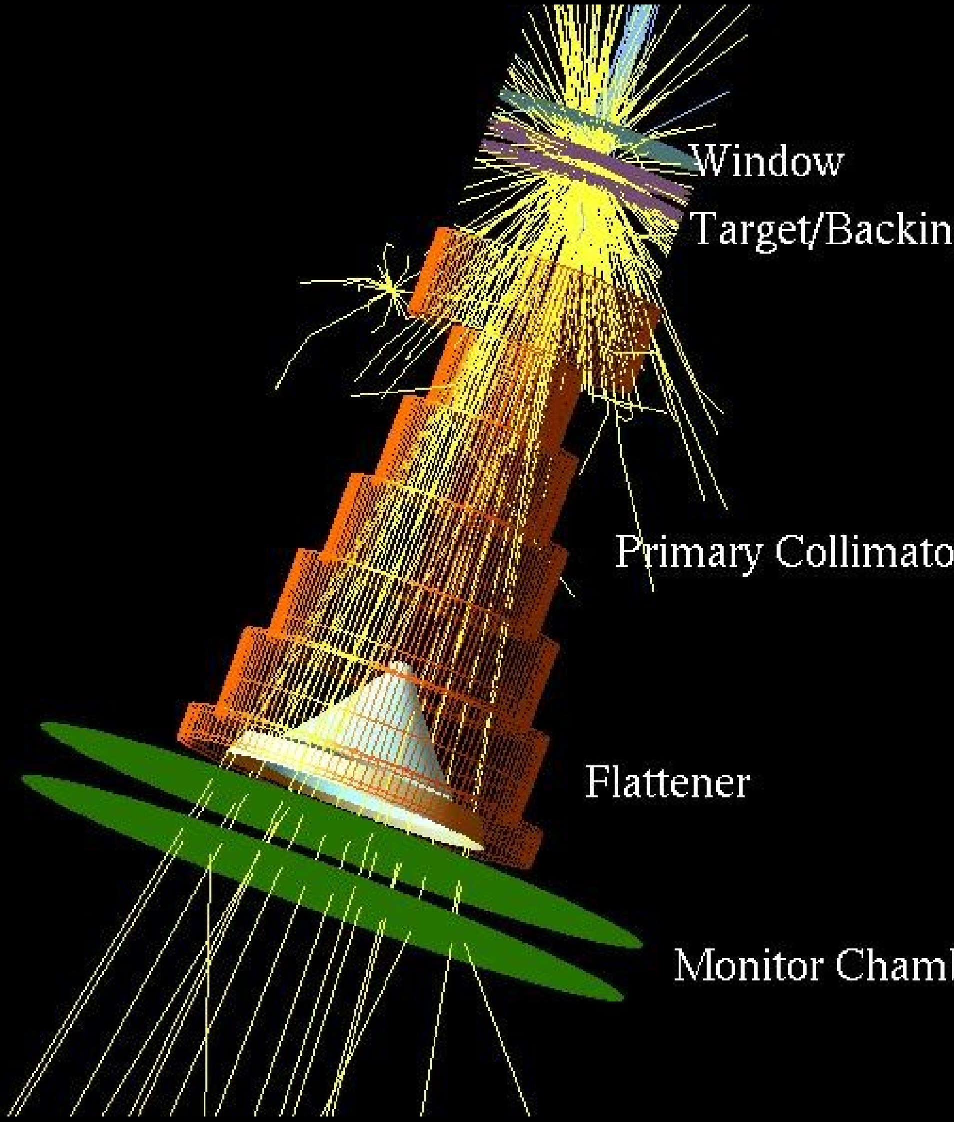
TrueBeam



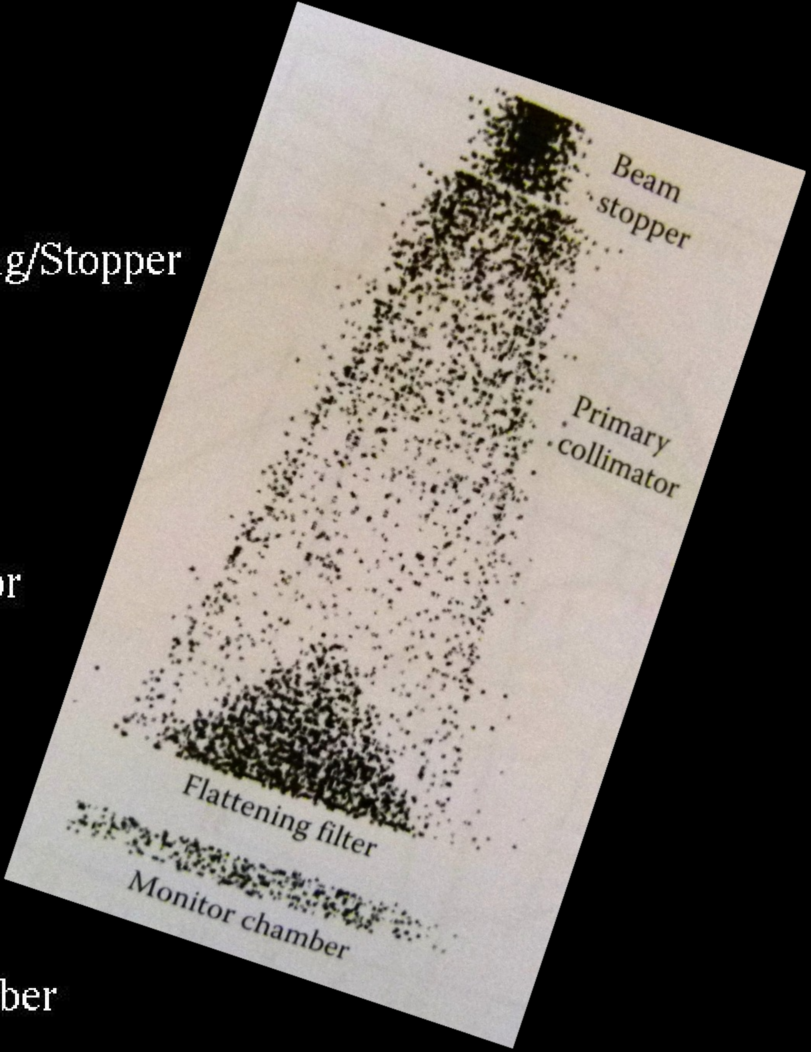
Tomotherapy

CyberKnife

X-ray Treatment Head

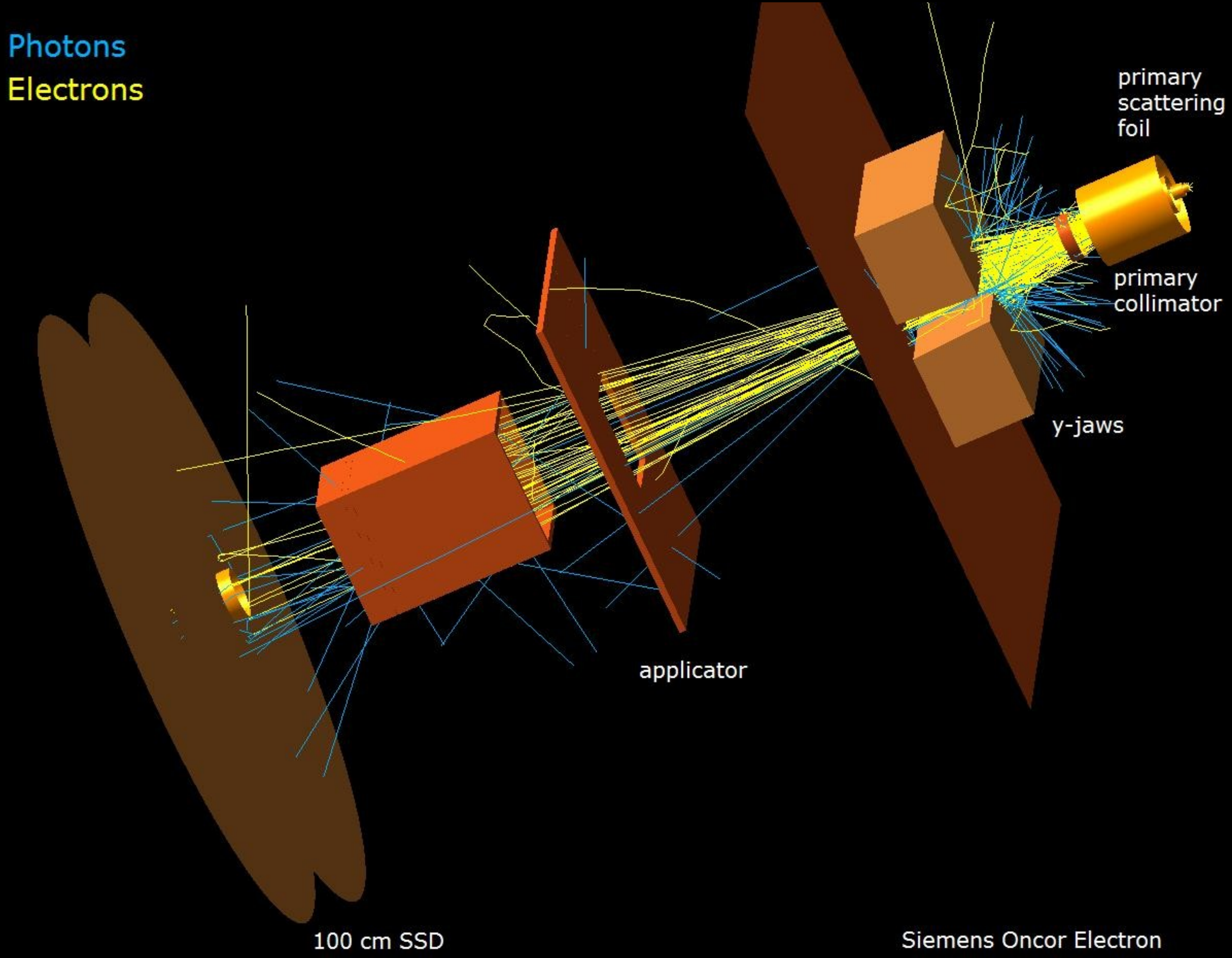


Sources of scattered photons



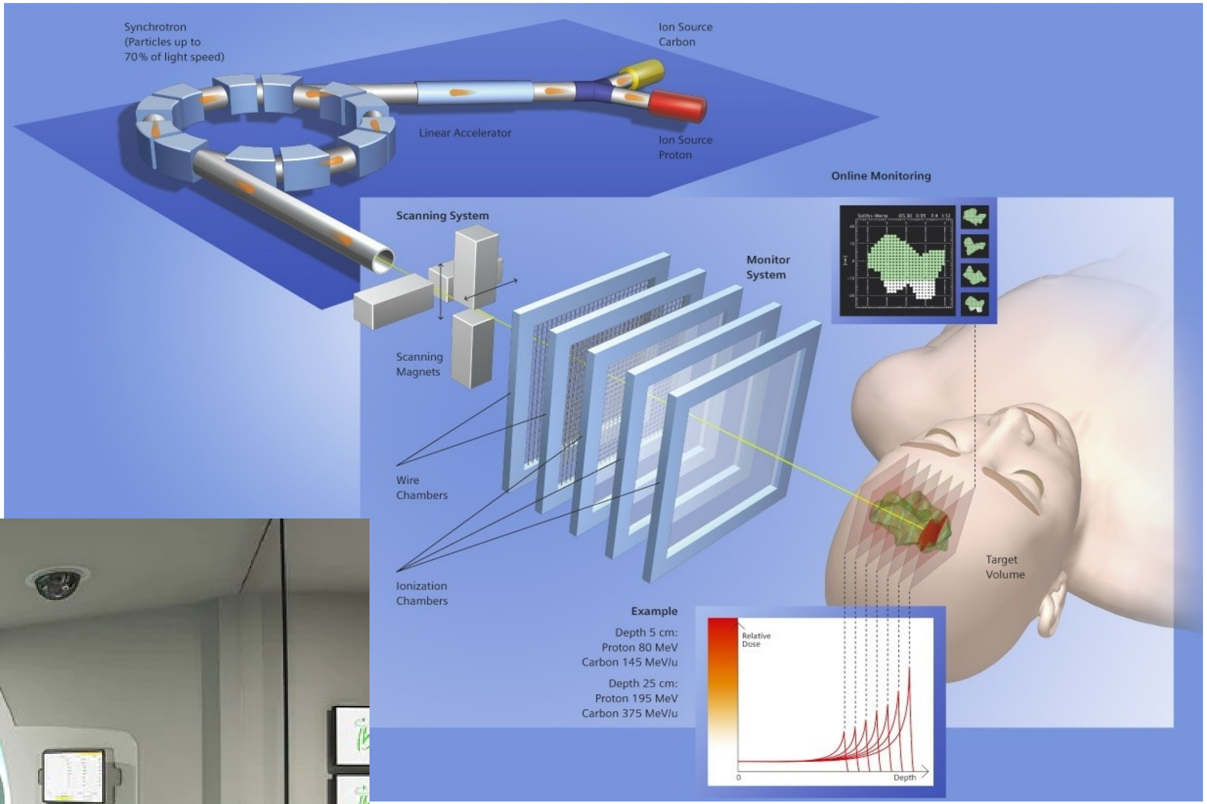
Seco and Verhaegen

Electron Treatment Head



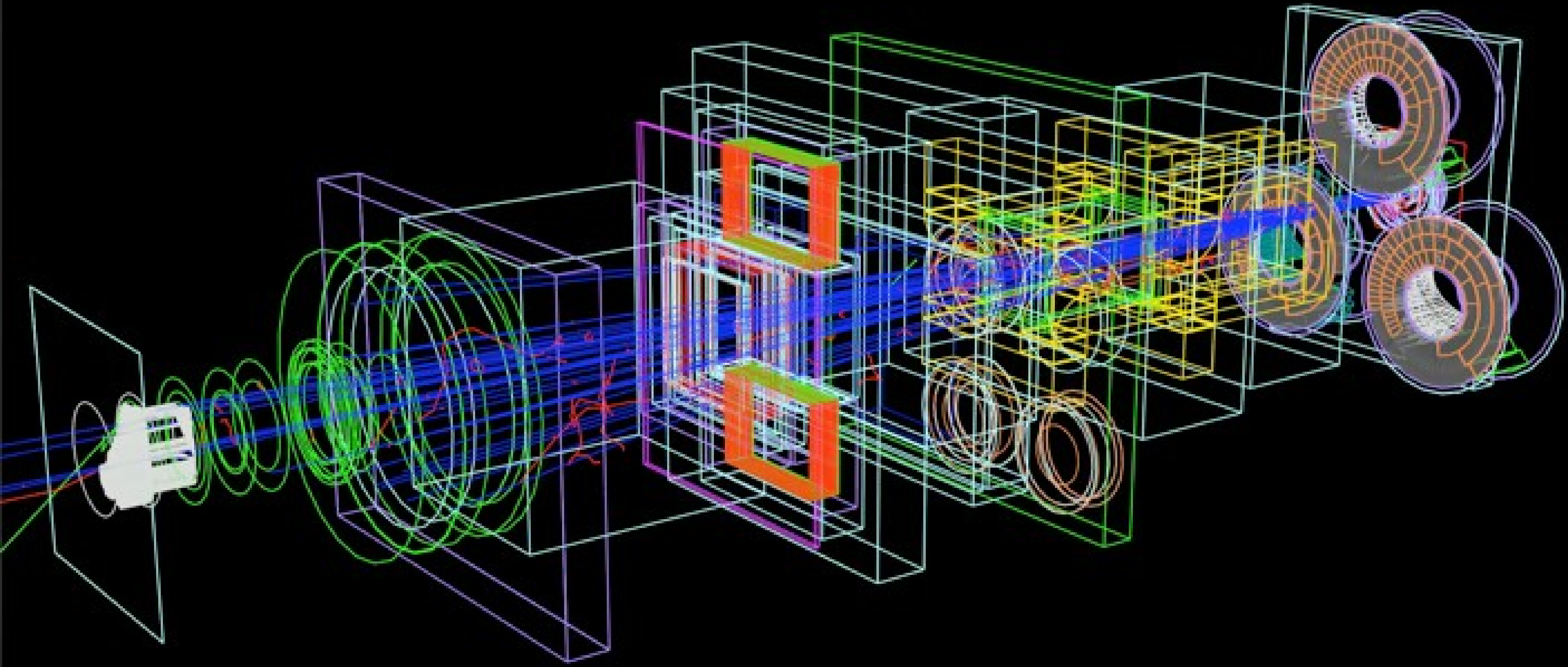
Proton and Ion-Beam Radiotherapy

Source: GSI/HIT



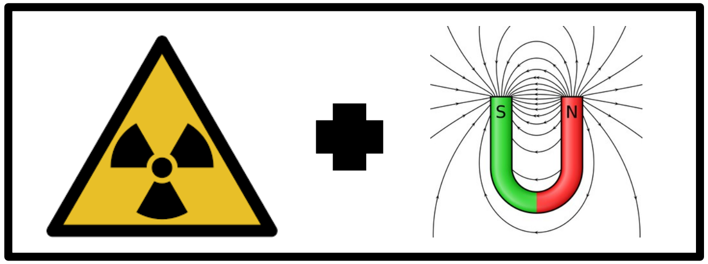
Source: Philips/IBA

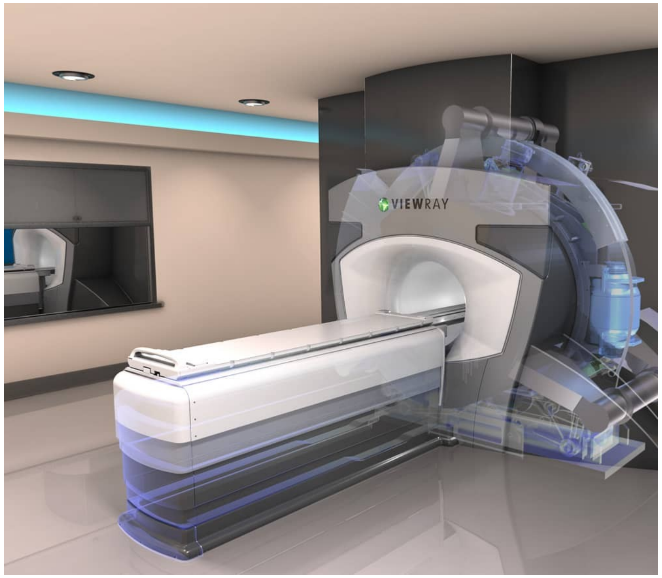
Proton beam simulation at MGH



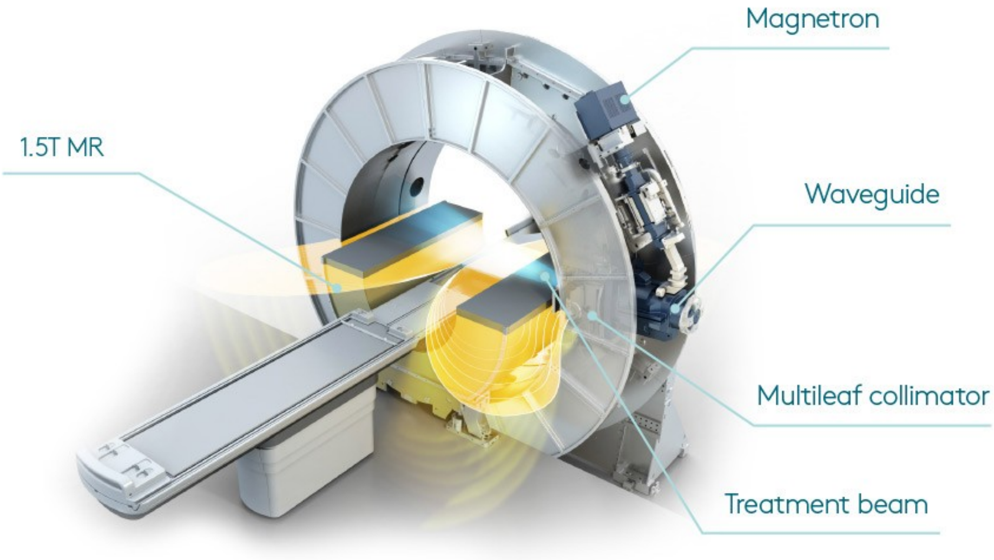
Monte Carlo for simulation of radiation transport in magnetic fields

MR-guided Radiotherapy



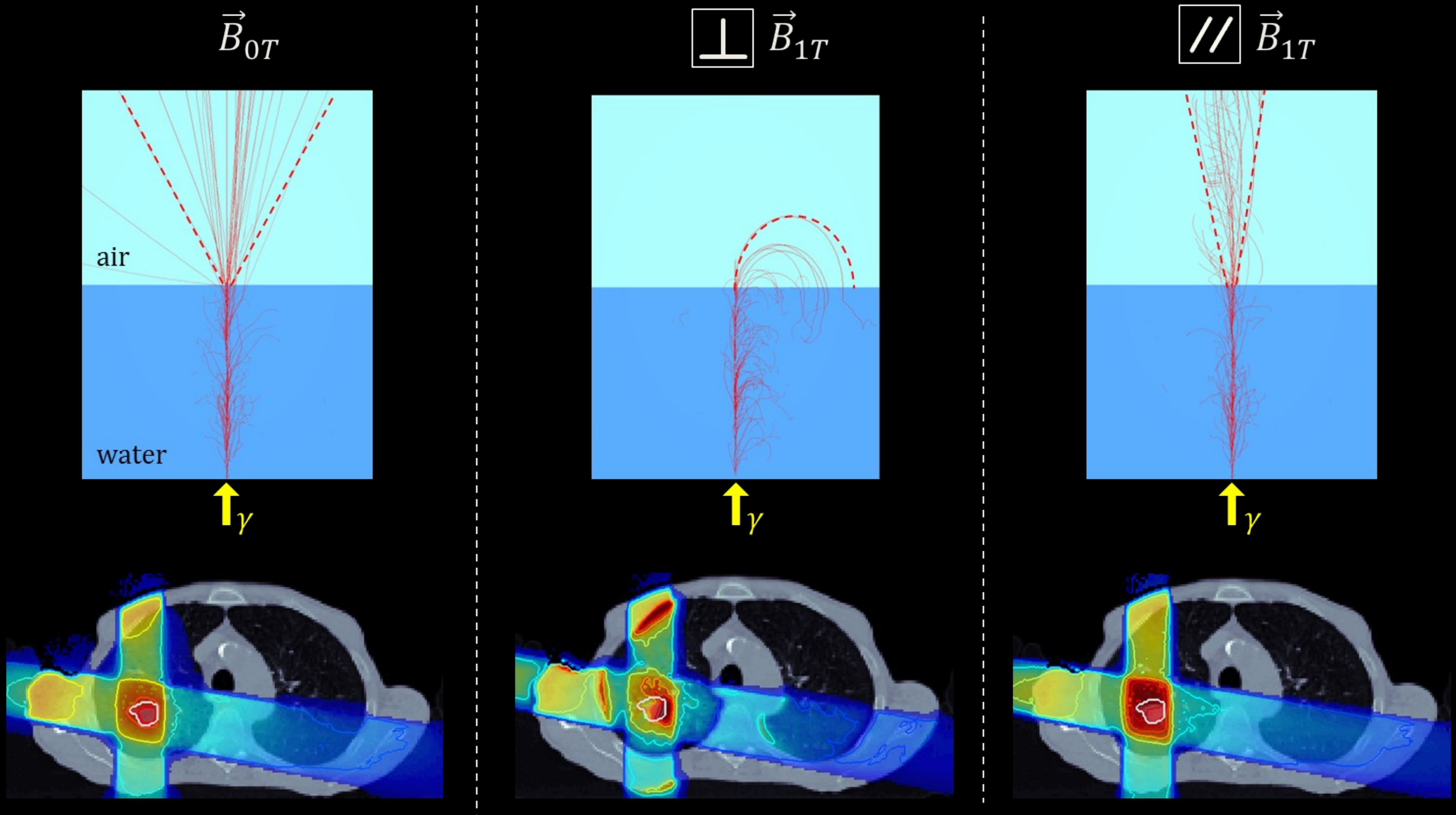


Source: https://viewray.com/



Source: https://mrrt.elekta.com/elekta-mr-linac/

High effect of magnetic field on dose deposition in lung



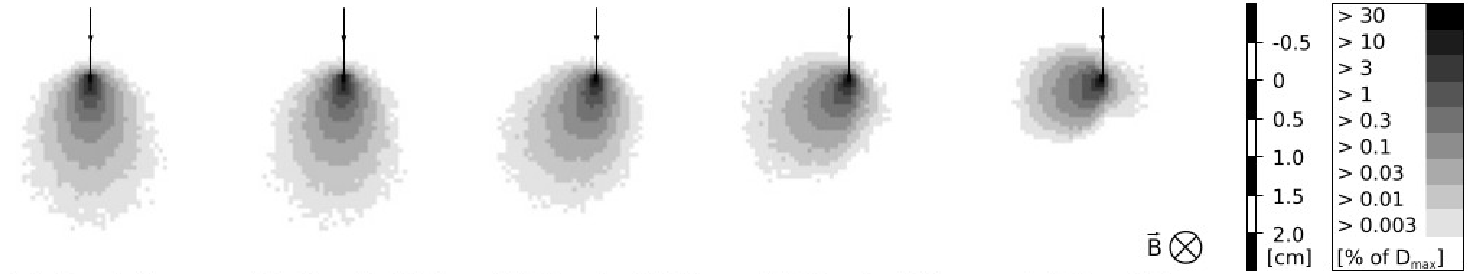
By courtesy of Oliver Schrenk

Photon beam in transverse B-field

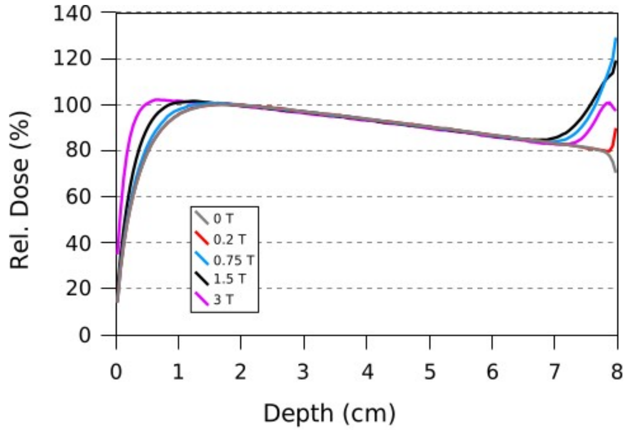
Transverse magnetic field leads to asymmetrical point-spread kernel

→ shift of build-up distance

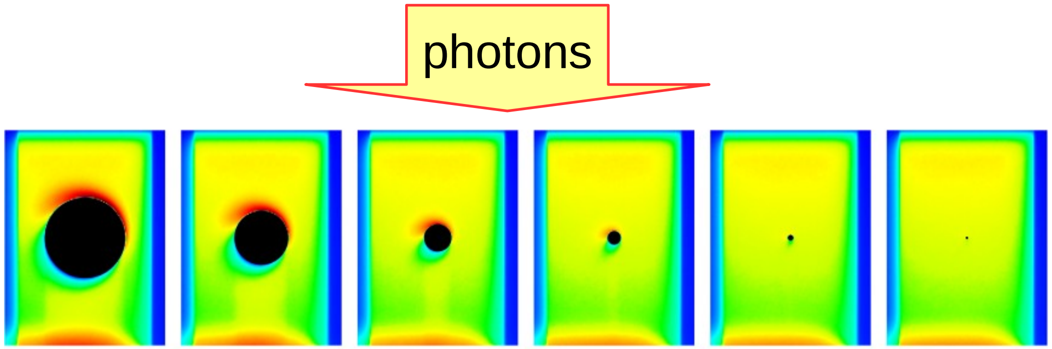
→ electron-return effect (ERE) affecting surface dose (skin, cavities)



(a) B = 0 T (b) B = 0.2 T (c) B = 0.75 T (d) B = 1.5 T (e) B = 3 T



(a) 5×5 cm^2, central axis

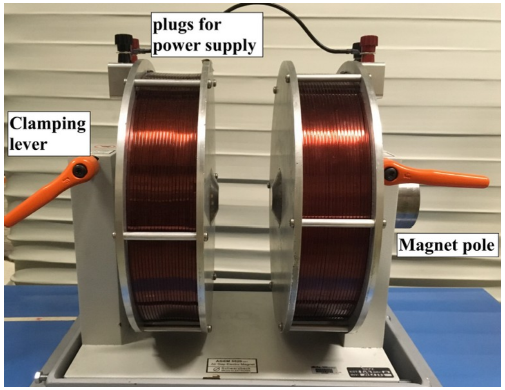


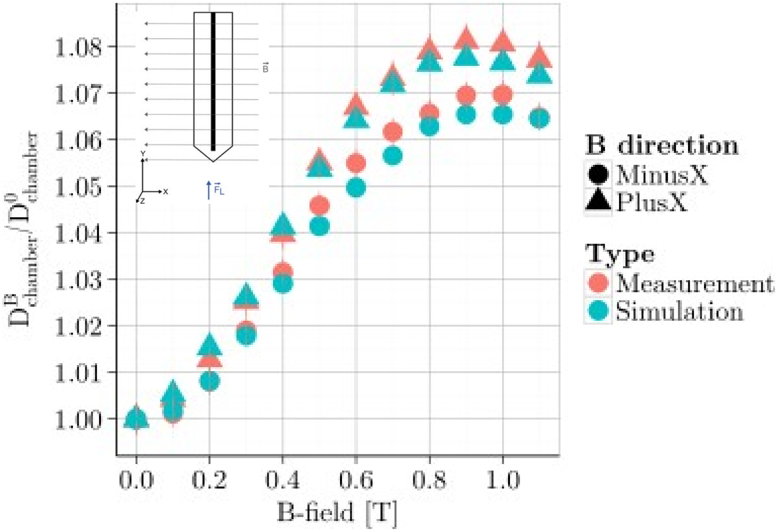
(c) B = 1 .5T

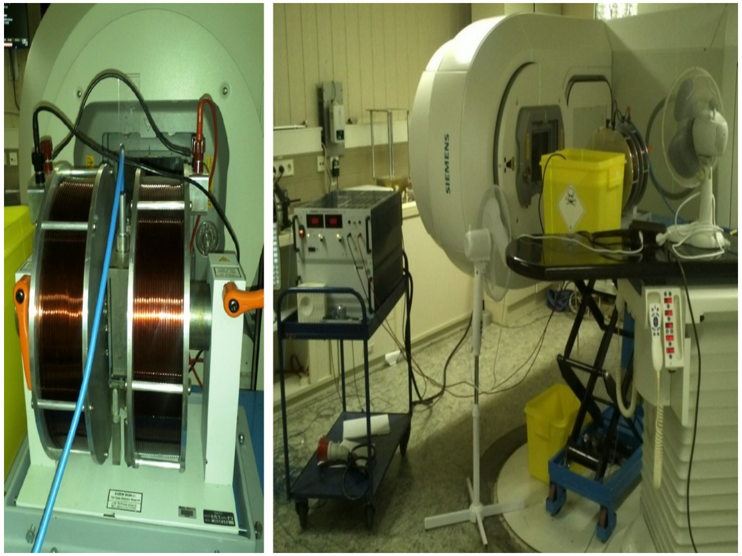
A J E Raaijmakers et al 2008 Phys. Med. Biol. 53 909

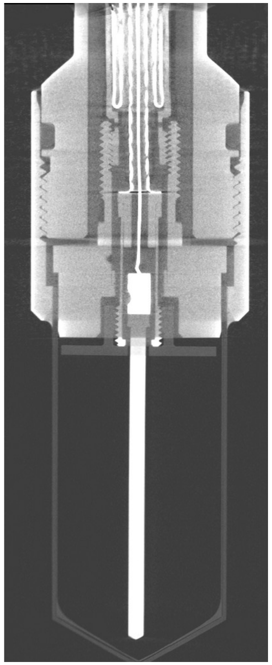
Chamber response in MR-guided RT

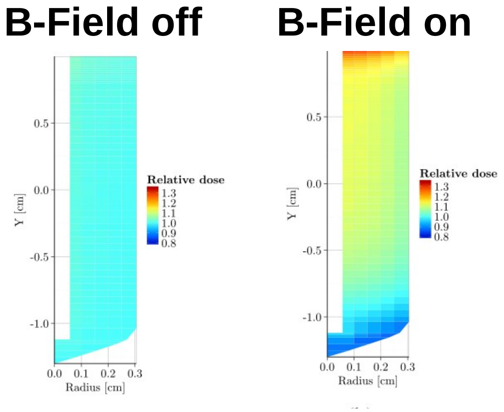
Monte Carlo plays a key role in understanding and estimating the effect of magnetic field







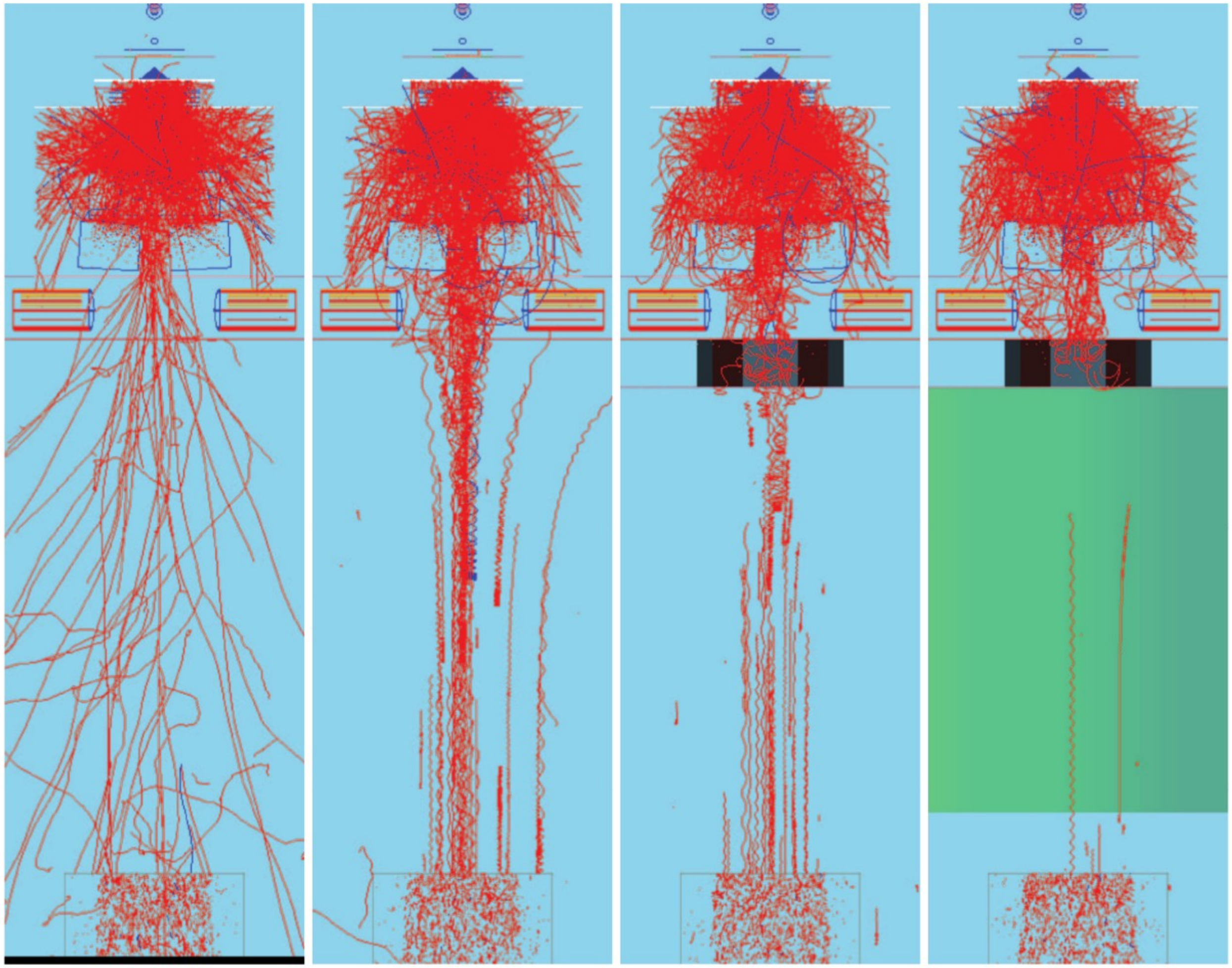



B-Field off

B-Field on

C K Spindeldreier et al 2017 Phys. Med. Biol. 62 6708

Estimation of Electron Contamination in In-line B-field



$B = 0\ \mathrm{T}$ $B = B_{MRI}$ $B = B_{MRI+ECD}$ $B = B_{MRI+ECD} + \mathrm{He}$

Oborn et al. Med. Phys. 41 (5), May 2014

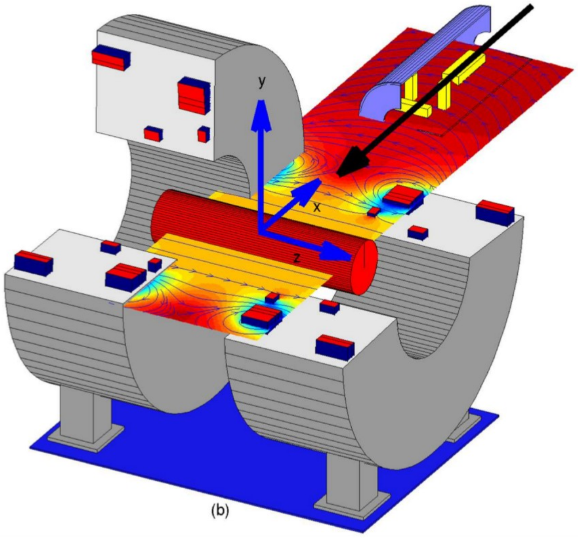
Proton beam delivery in fringe field (I)

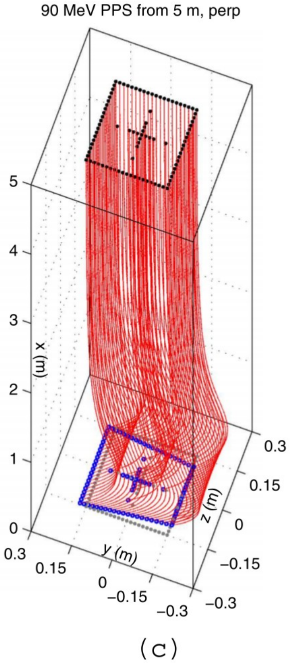
Perpendicular B-field

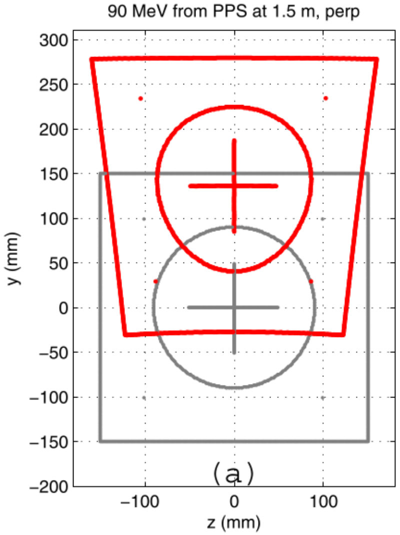
- The main MRI field and near fringe field act as the strongest to deflect the protons in a consistent direction.

- Off-axis protons are slightly deflected toward or away from the central axis in the direction perpendicular to the main deflection direction

→ distortion of the phase space pattern







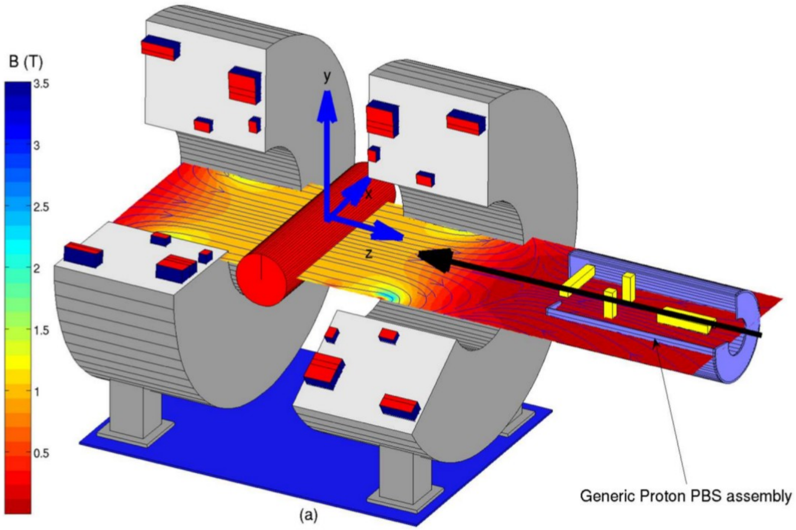
Oborn et al. Med. Phys. 42 (5), May 2015

Proton beam delivery in fringe field (II)

In-line B-field

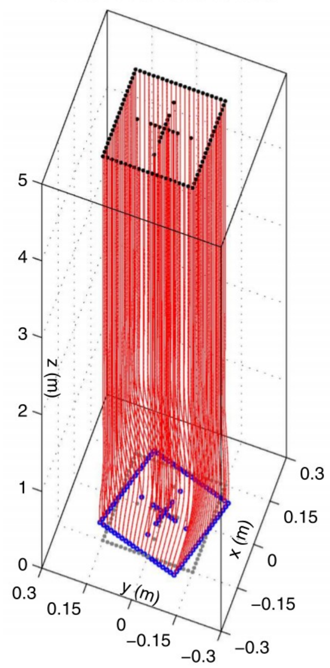
- Radial symmetry of the solenoidal style fringe field acts to rotate the protons around the beam’s central axis.

- A minor focusing toward the beam’s central axis is also present.



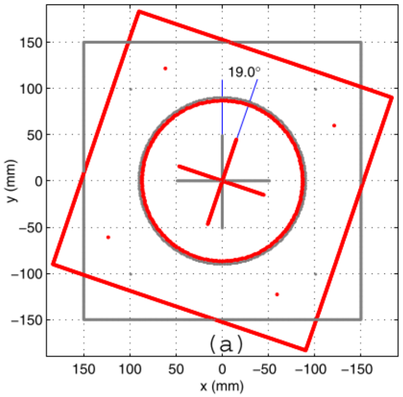
(a)

90 MeV PPS from 5 m, inline



(b)

90 MeV from PFS at 1.5 m, inline



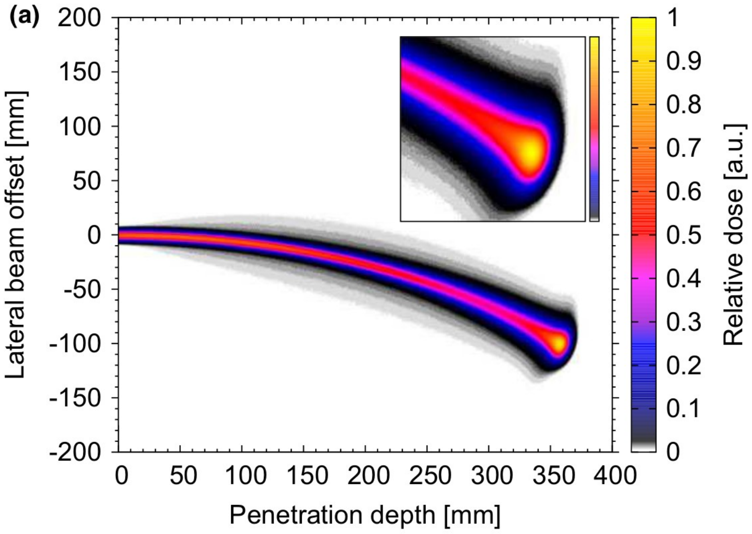
(a)

Oborn et al. Med. Phys. 42 (5), May 2015

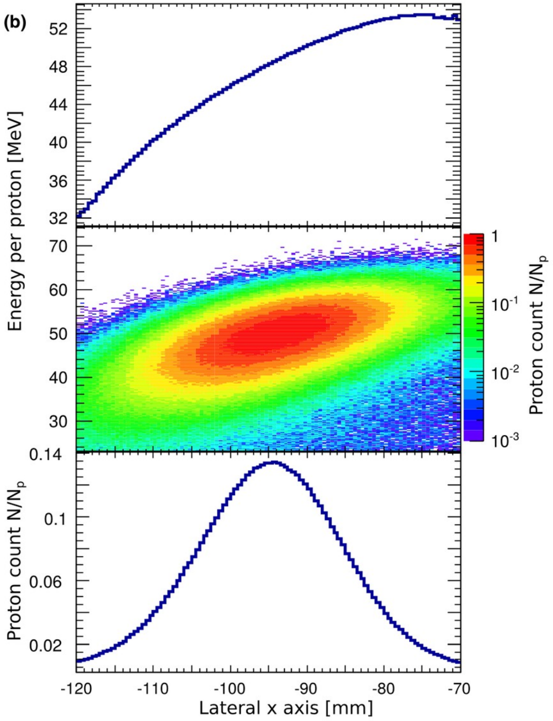
Proton dose distribution in B-field

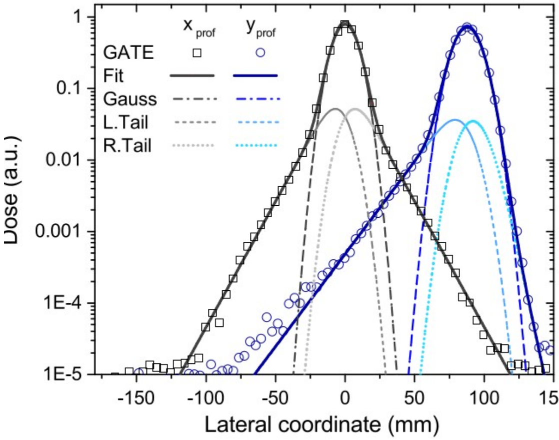
Distortions on dose distribution in perpendicular B-field

Deflection of proton beam results in shift of the Bragg peak position laterally and in depth with lateral spectral separation of protons.



Fuchs et al., Med Phys 44 2017

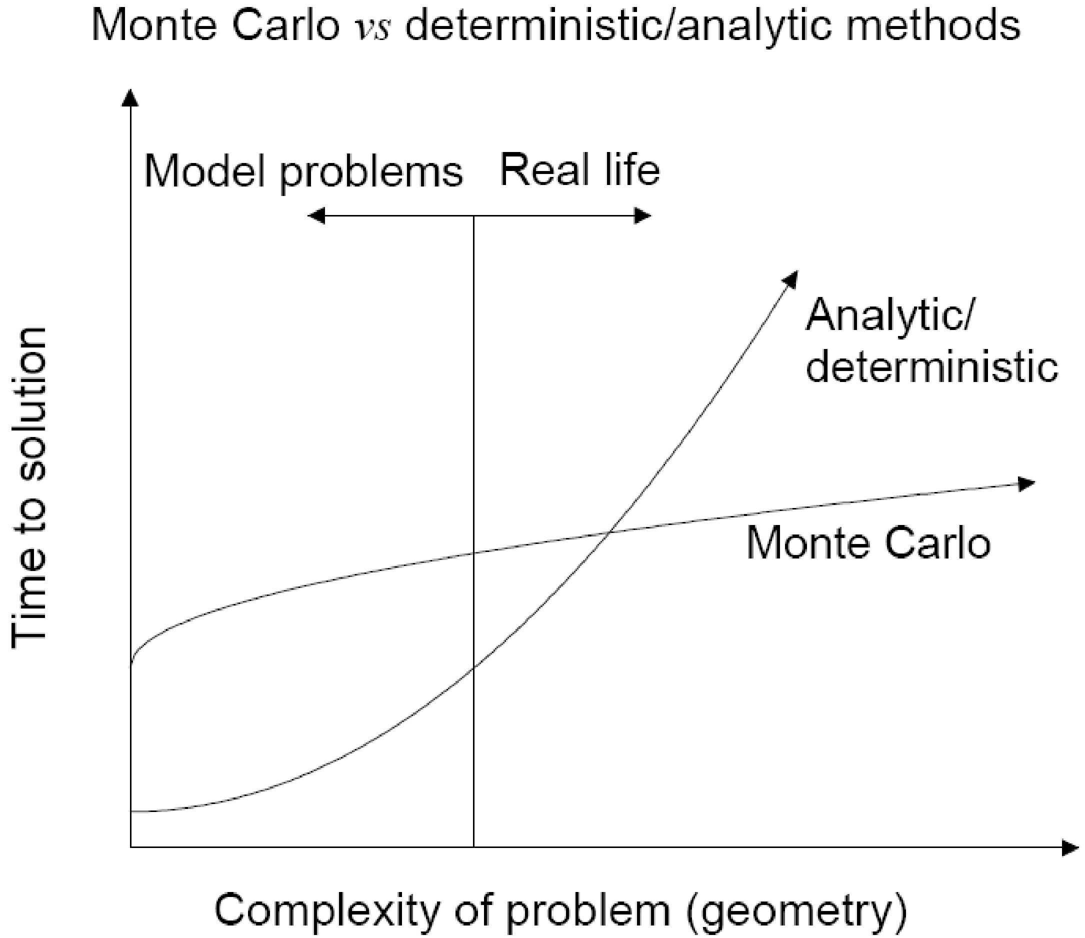




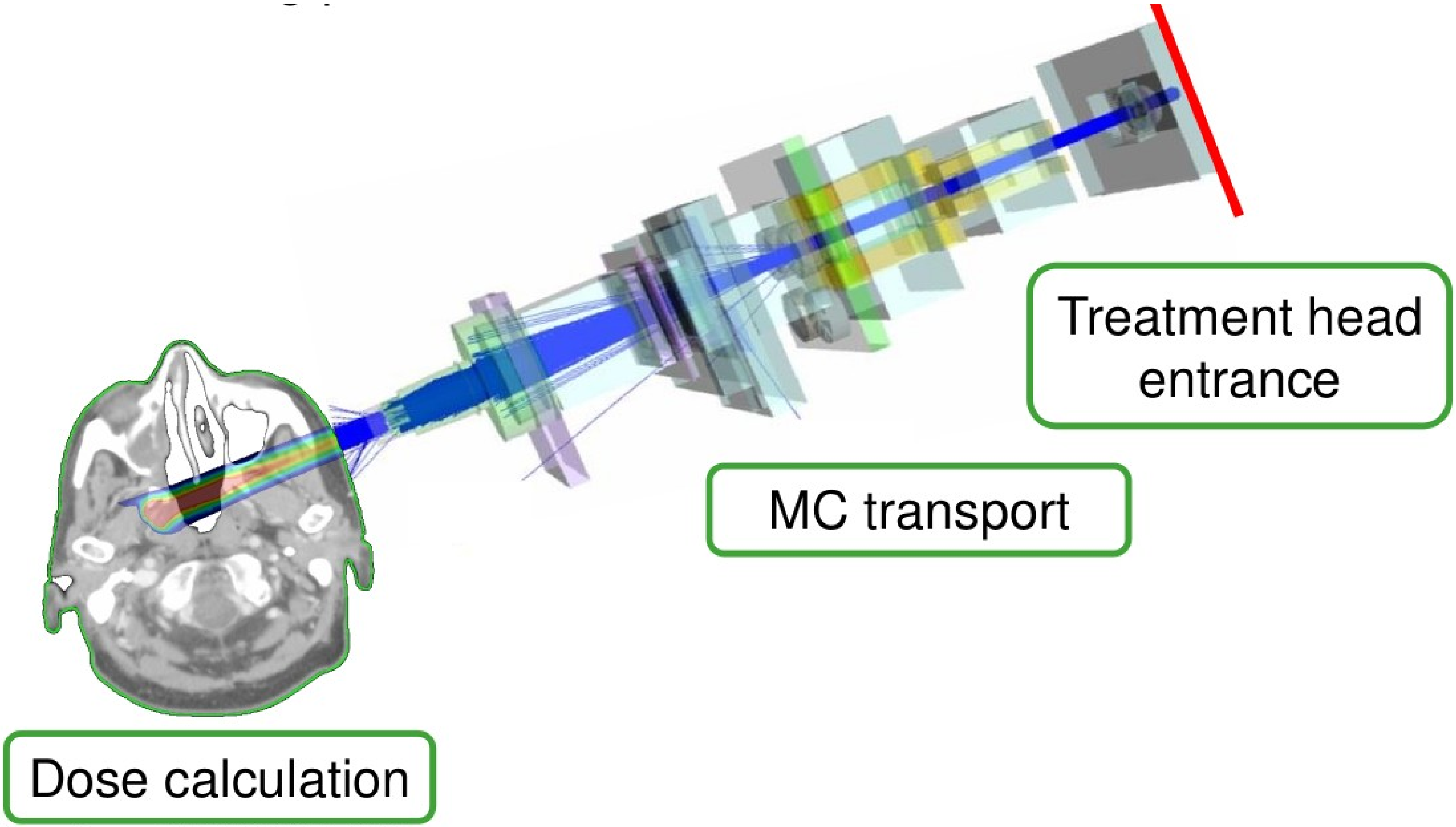
Padilla-Cabal et al Med Phys 45 (5), May 2018

Analytical/Deterministic Dose Calculation vs Monte Carlo Method

For complex geometrical problems as the transport of radiation through a patient, Monte Carlo provides a faster solution than analytical methods.



Extremely difficult to solve analytically, but a trivial task for Monte Carlo!

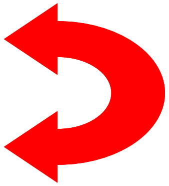


Adapted from Paganetti, PMB 57 (11) 2012

Advantage of Monte Carlo

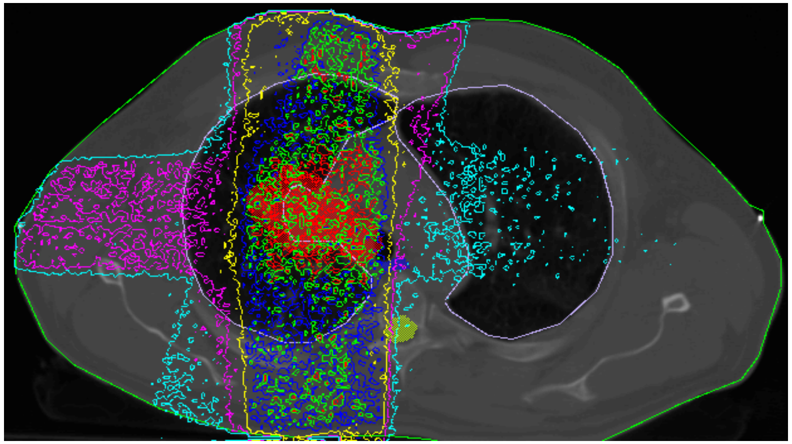
Accurately transport radiation through the treatment head and patient

Disadvantages of Monte Carlo



Calculation time

Statistical noise



But…

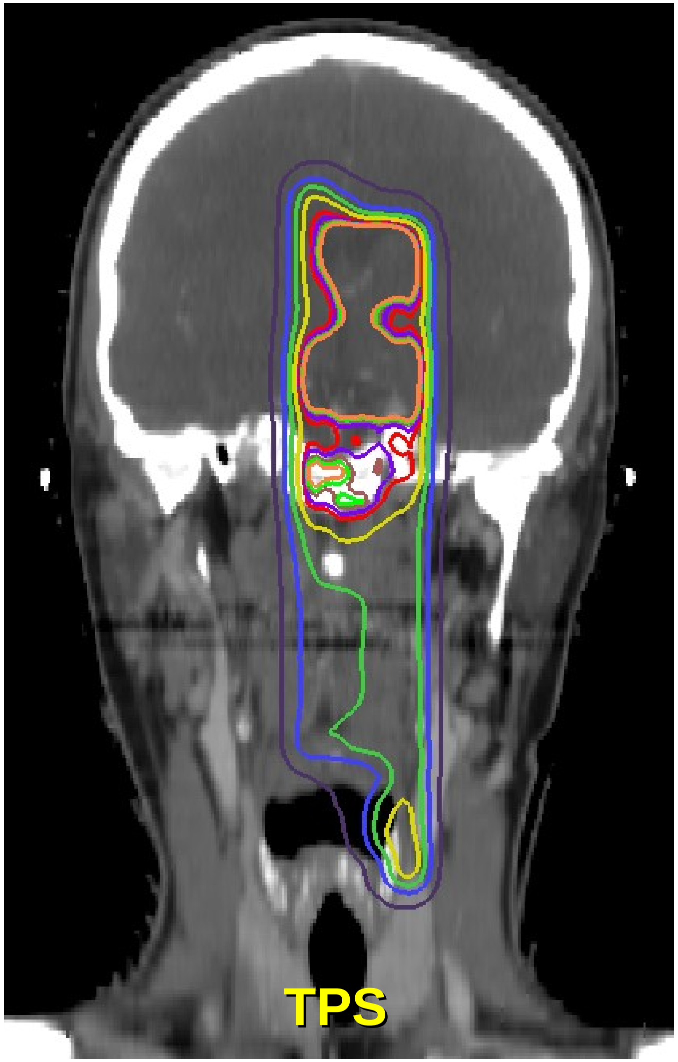
Monte Carlo codes are getting faster

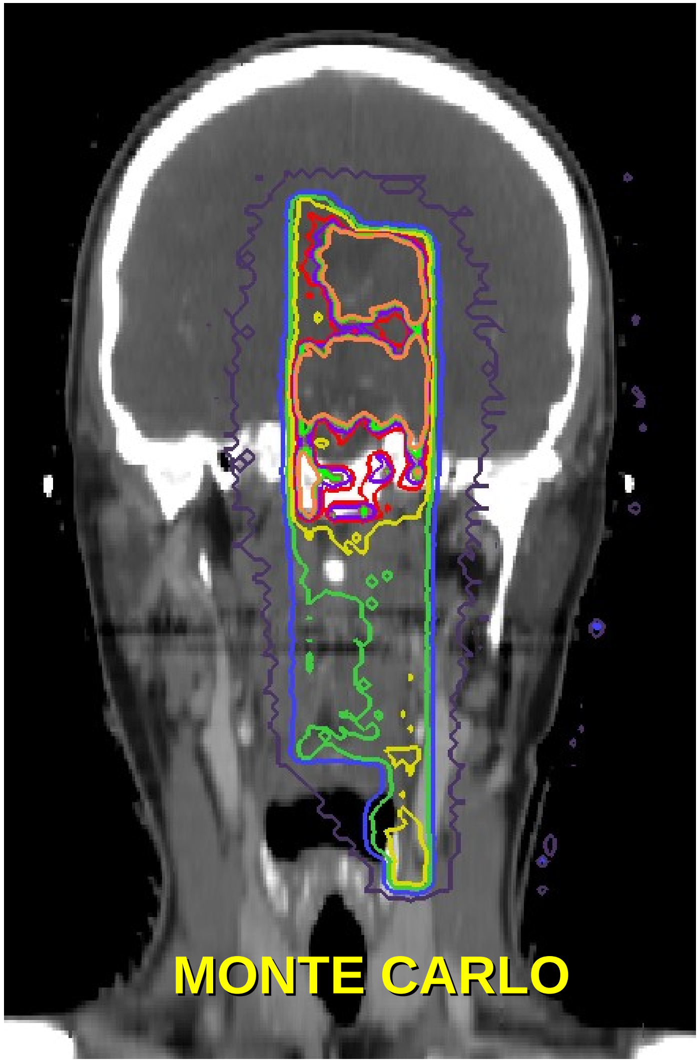
Computers are getting faster

Noise reduction methods are improving

By courtesy of João Seco

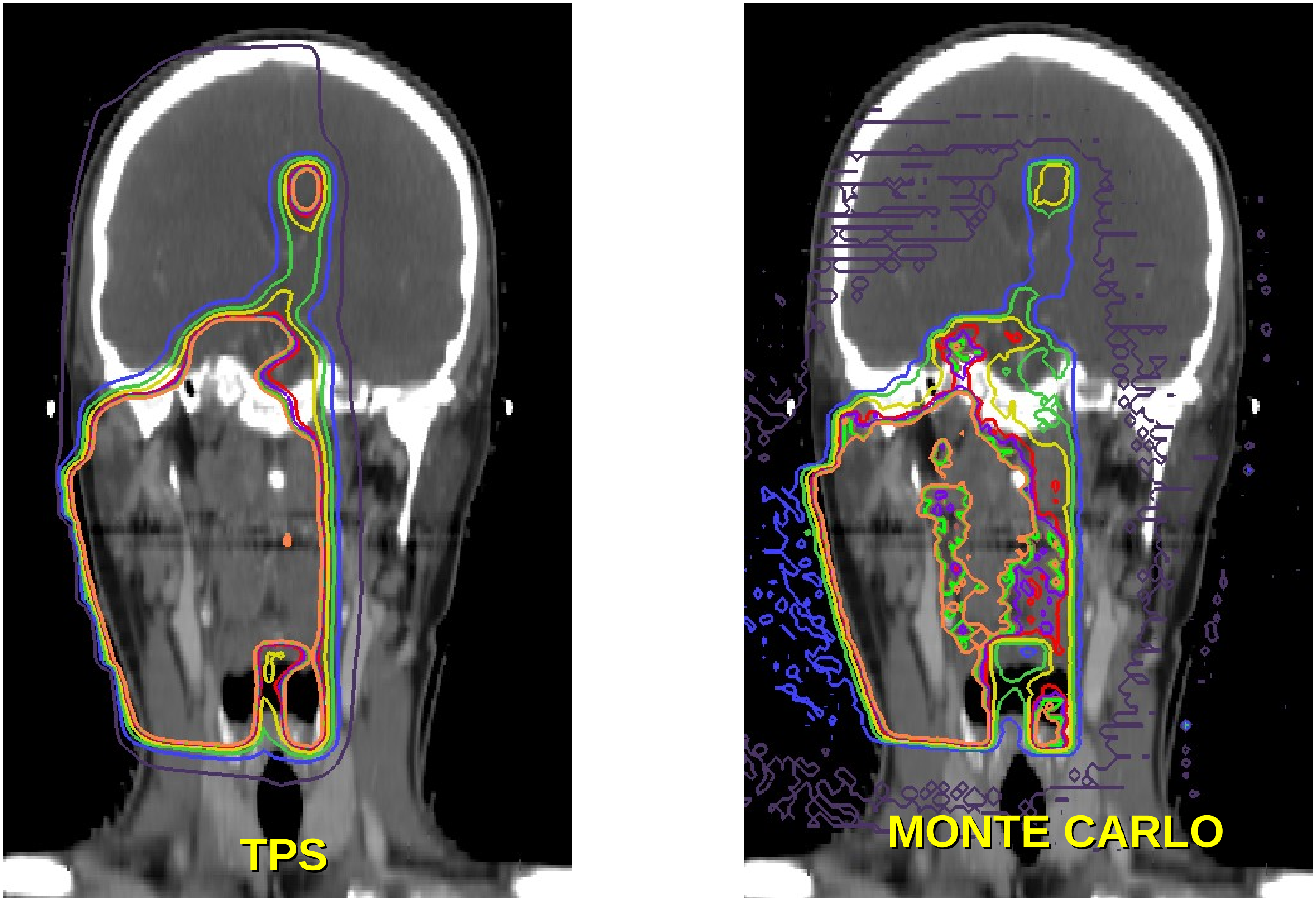
Patient MC Example 1: Head and Neck





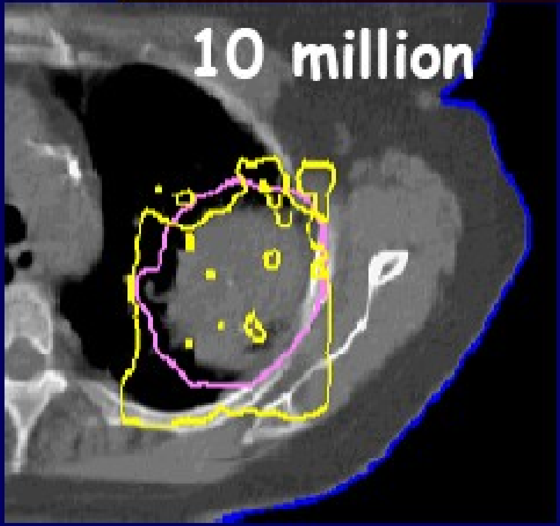
By courtesy of João Seco

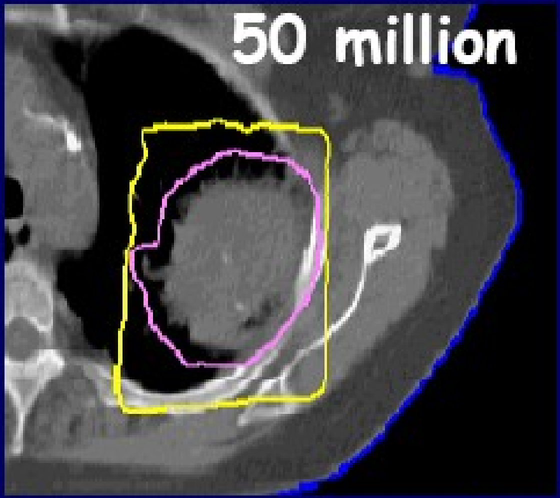
Patient MC Example 2: Head and Neck

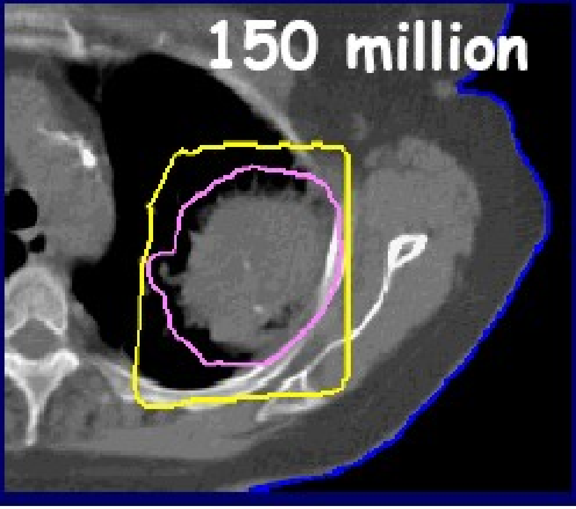


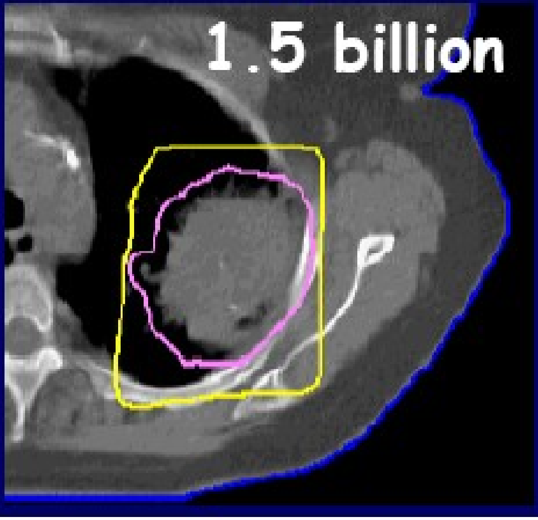
By courtesy of João Seco

Effect of uncertainties on the 95% IDL


10 million

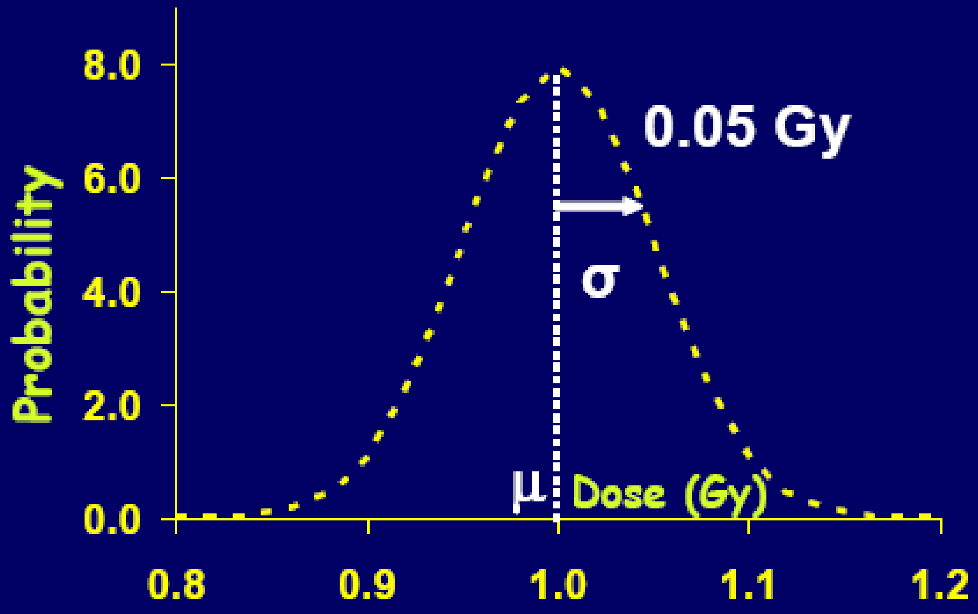

50 million


150 million


1.5 billion

Statistical uncertainties

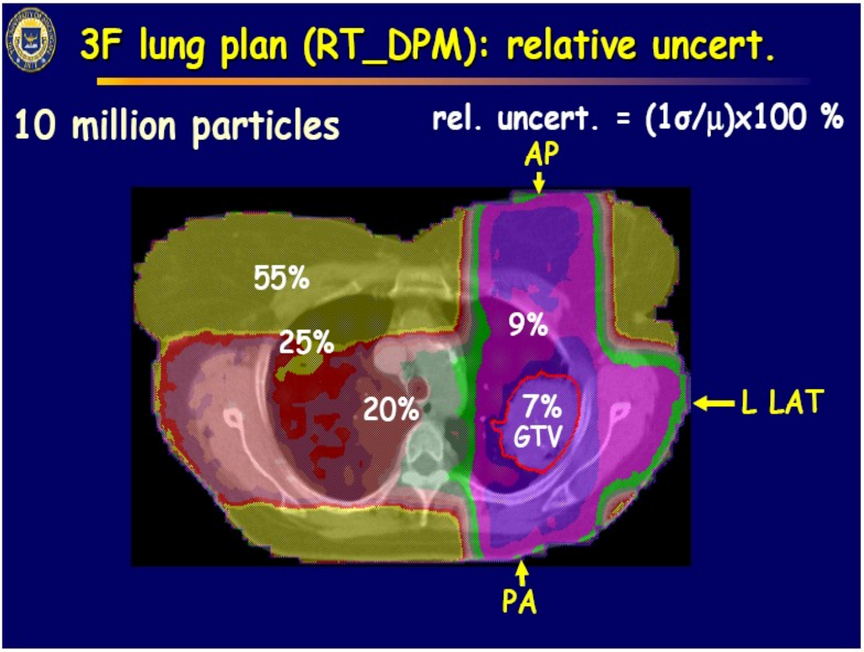
“Jittery” isodose lines due to the stochastic nature of the MC method are quite different from dose distributions computed with conventional (deterministic) algorithms



$\sigma \sim 1/\sqrt{N}$,

N= total no. of particles simulated

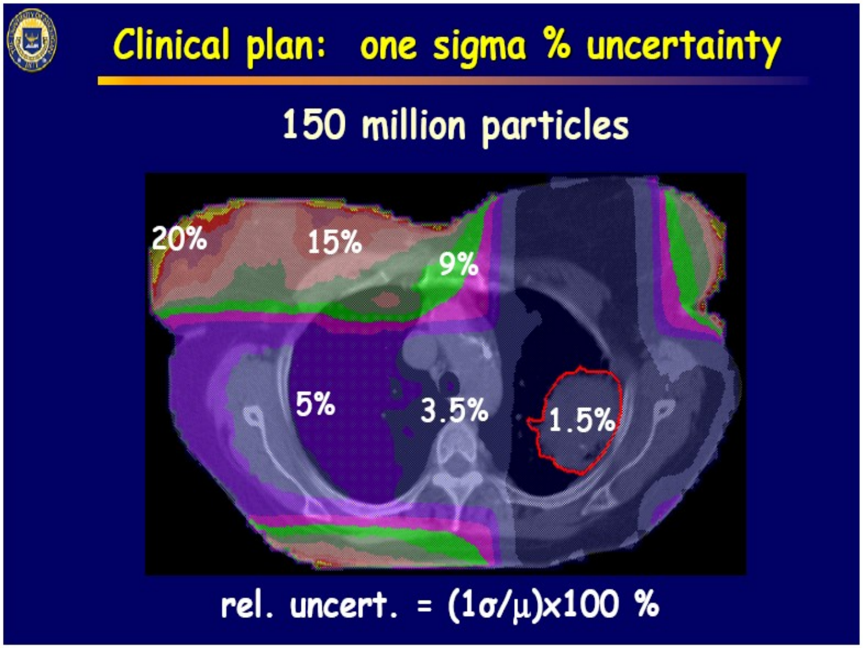
In tx planning, Relative uncertainty $= \sigma/\mu$



3F lung plan (RT_DPM): relative uncert.

10 million particles

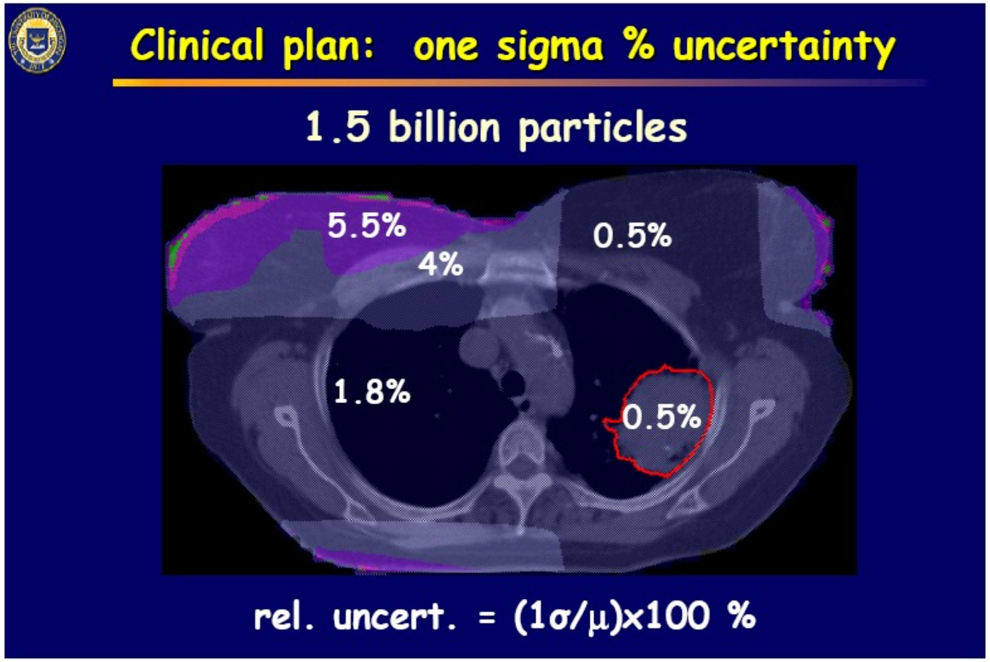
rel. uncert. = (1σ/μ)x100 %



Clinical plan: one sigma % uncertainty

150 million particles

rel. uncert. = (1σ/μ)x100 %



Clinical plan: one sigma % uncertainty

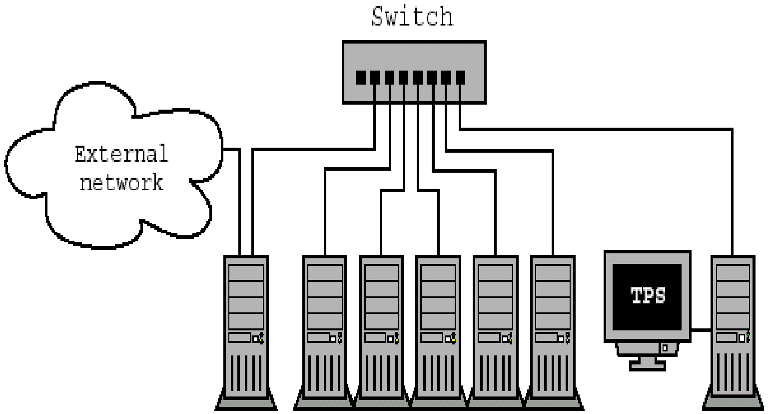
1.5 billion particles

rel. uncert. = (1σ/μ)x100 %

Monte Carlo and the Problem of Statistical Uncertainty

- **Con:** Computationally inefficient, requires long computational time
- **Pro:** Monte Carlo simulations can be made arbitrarily precise
  Monte Carlo simulations can be parallelized

Linux Beowulf cluster built for parallel Monte Carlo simulations (Prof Seco)



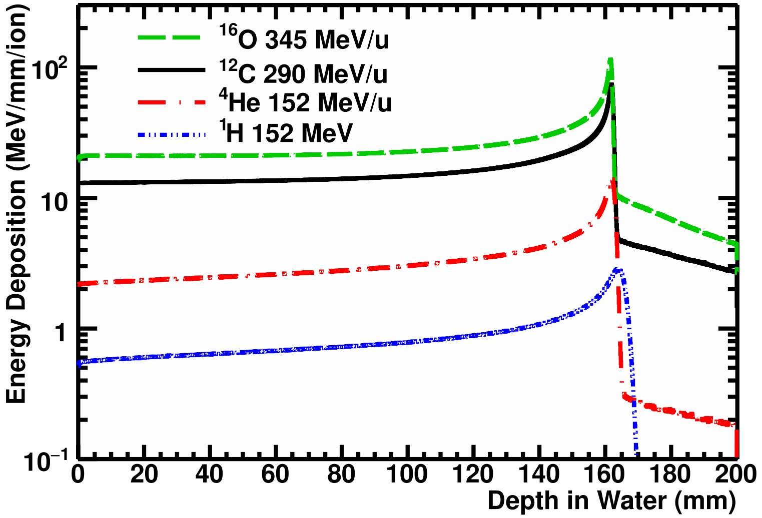
Monte Carlo Particle Transport in Parallel Architectures

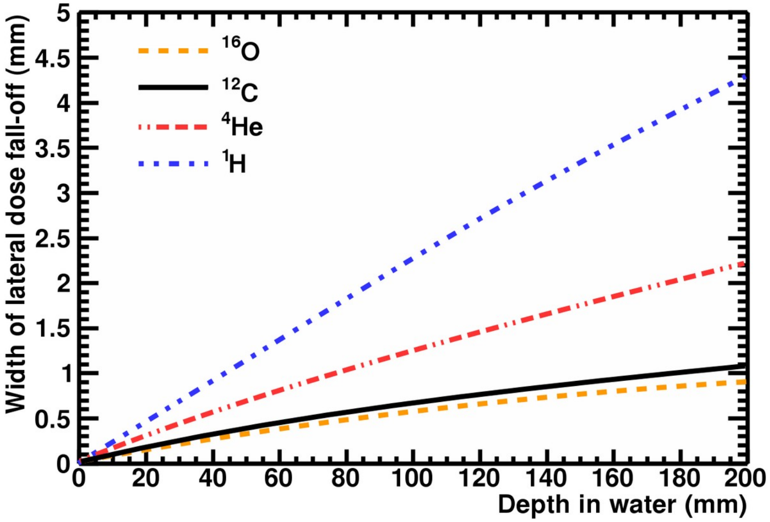
Modern Monte Carlo simulations make use of:

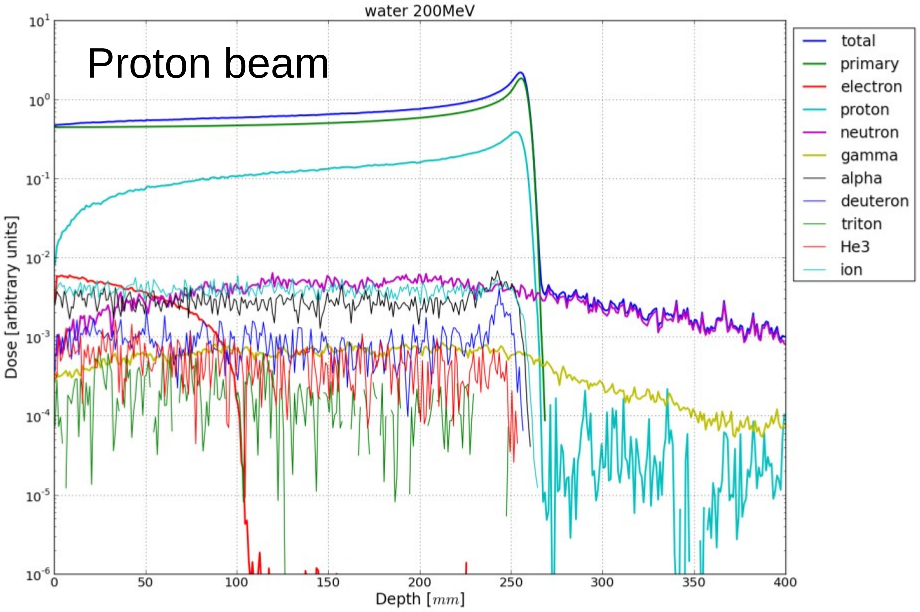
- High Performance Computers
- Graphics Processing Units

Monte Carlo for more than just dose calculation...

Radiotherapy with ion beams: Physical aspects

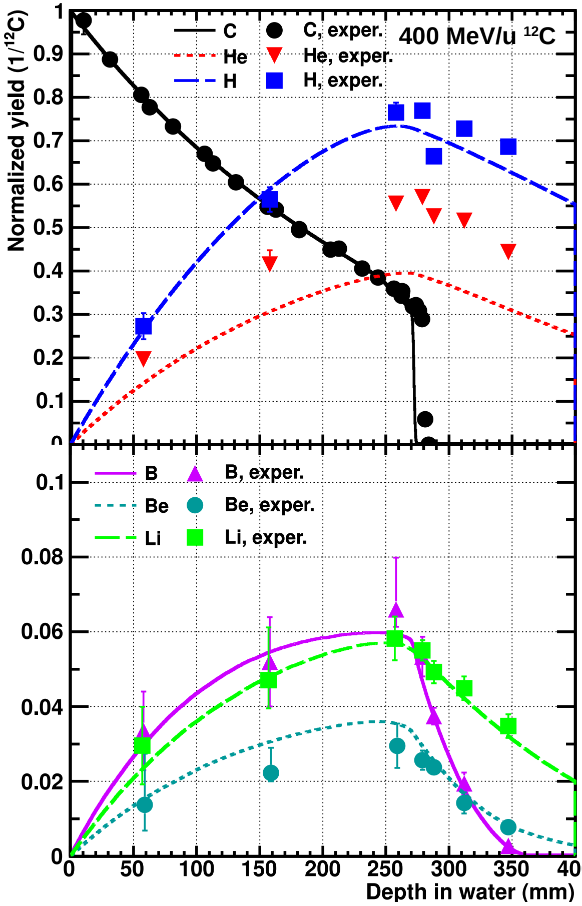


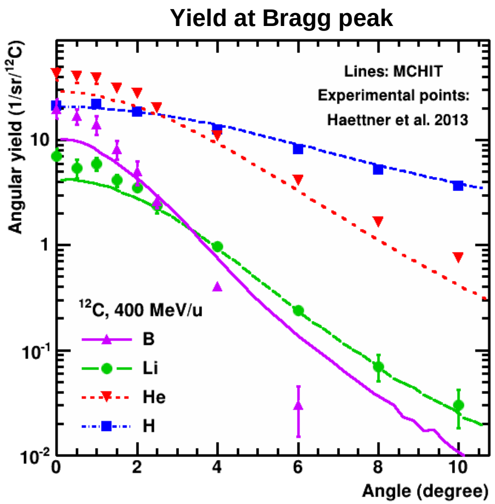




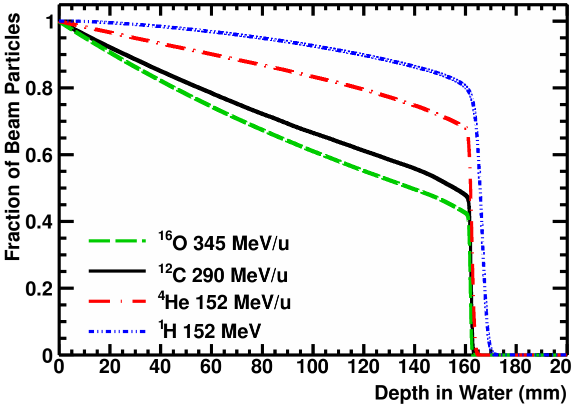
Nuclear fragmentation

Nuclear collisions of the primary ions with the nuclei of atoms in the medium attenuates the beam particles and creates a zoo of new particles.





The fragments are produced in a broad energy and angular distribution.

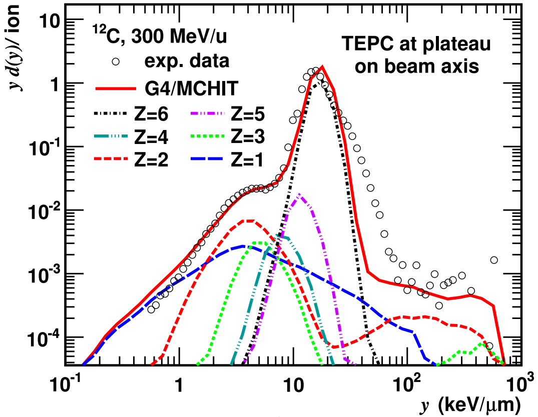


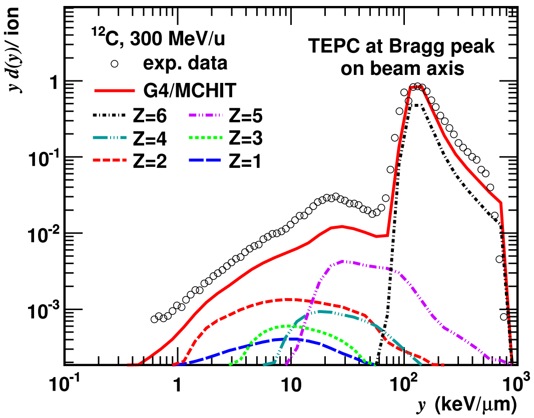
The impact of nuclear fragmentation is larger for heavier ions and increases with the ion range.

Burigo *et al.* (2013)

Radiation quality

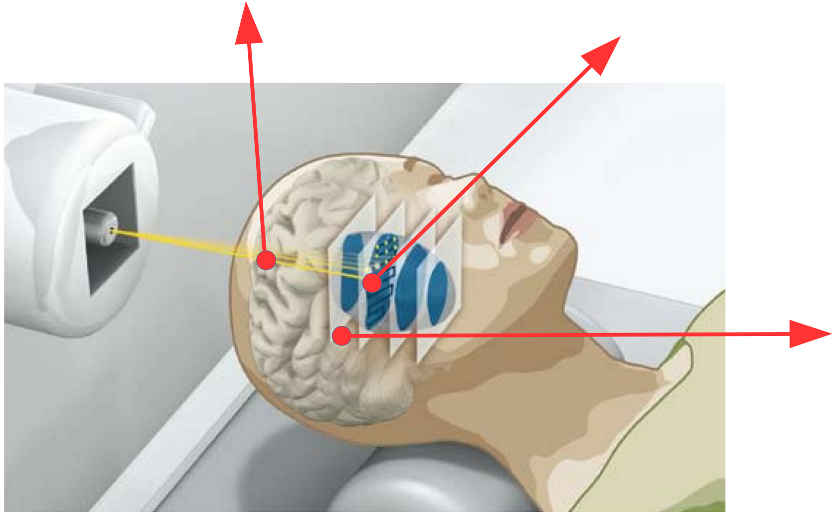
The LET and dose contribution of fragments changes with the position → variation in RBE

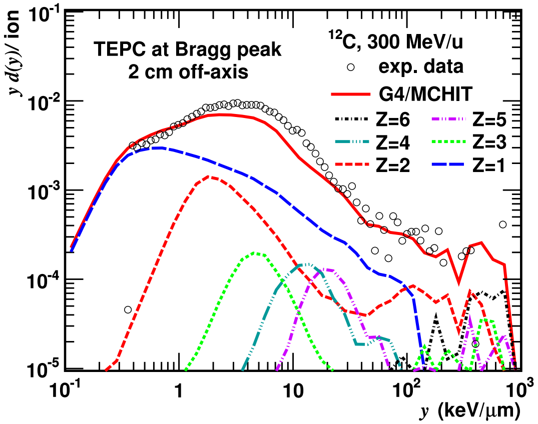




Larger variability of RBE in the tumor and healthy tissues is expected for heavier ions.

The radiation quality as a function of position in the patient can be reliably calculated with Monte Carlo.

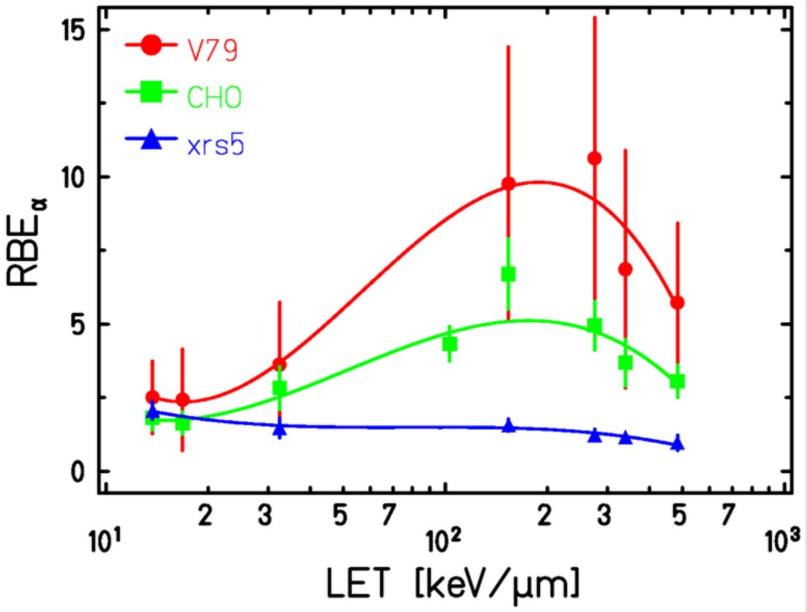




Burigo *et al.* (2014)

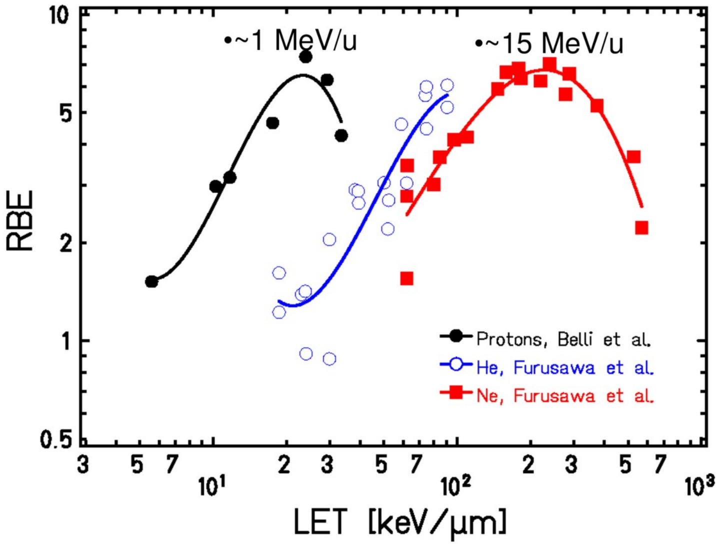
LET and Biological Effect

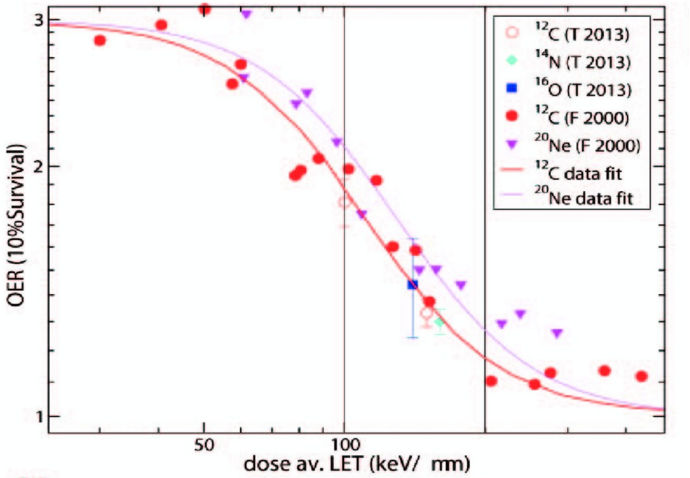
LET has been widely used to characterize the biological effect.



Weyrather *et al.* 1999

Scholz 2003

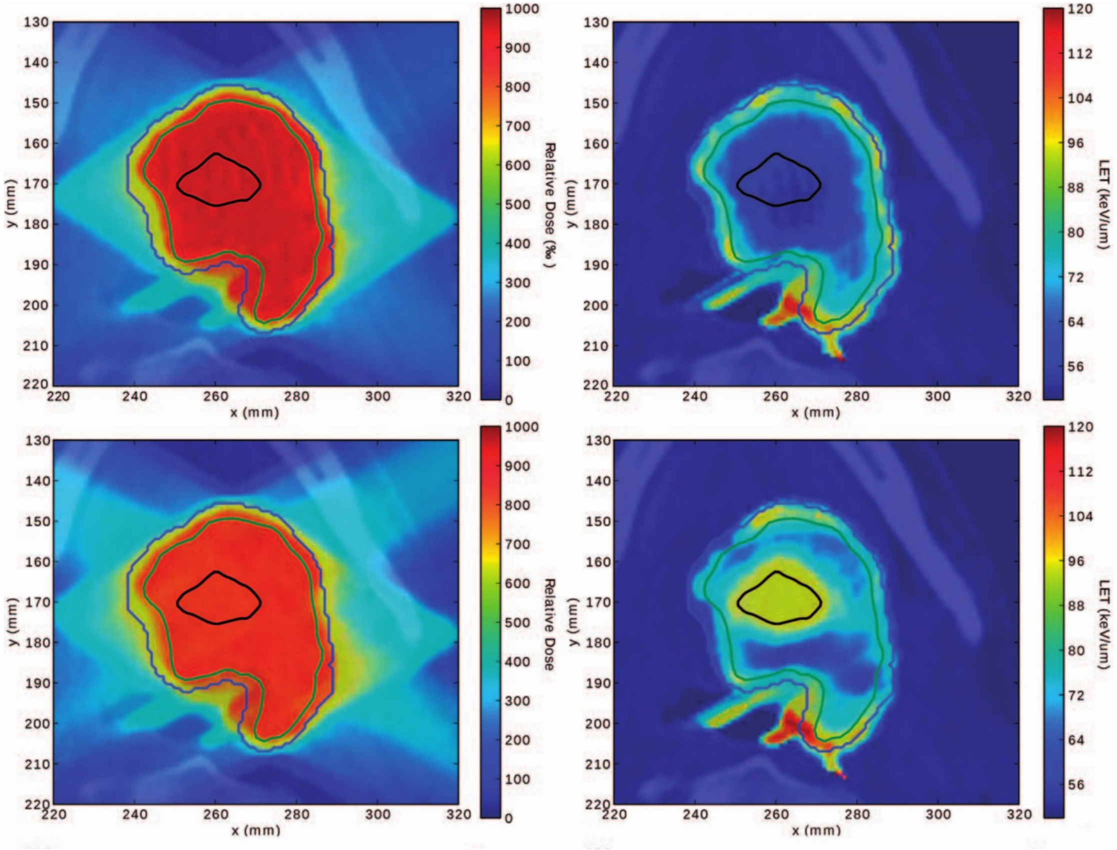




Tommasino *et al.* (2015)

LET-painting in the target

(Top) Dose and dose-average LET for a carbon-ion plan with four fields.
(Bottom) LET redistribution in the target volume.



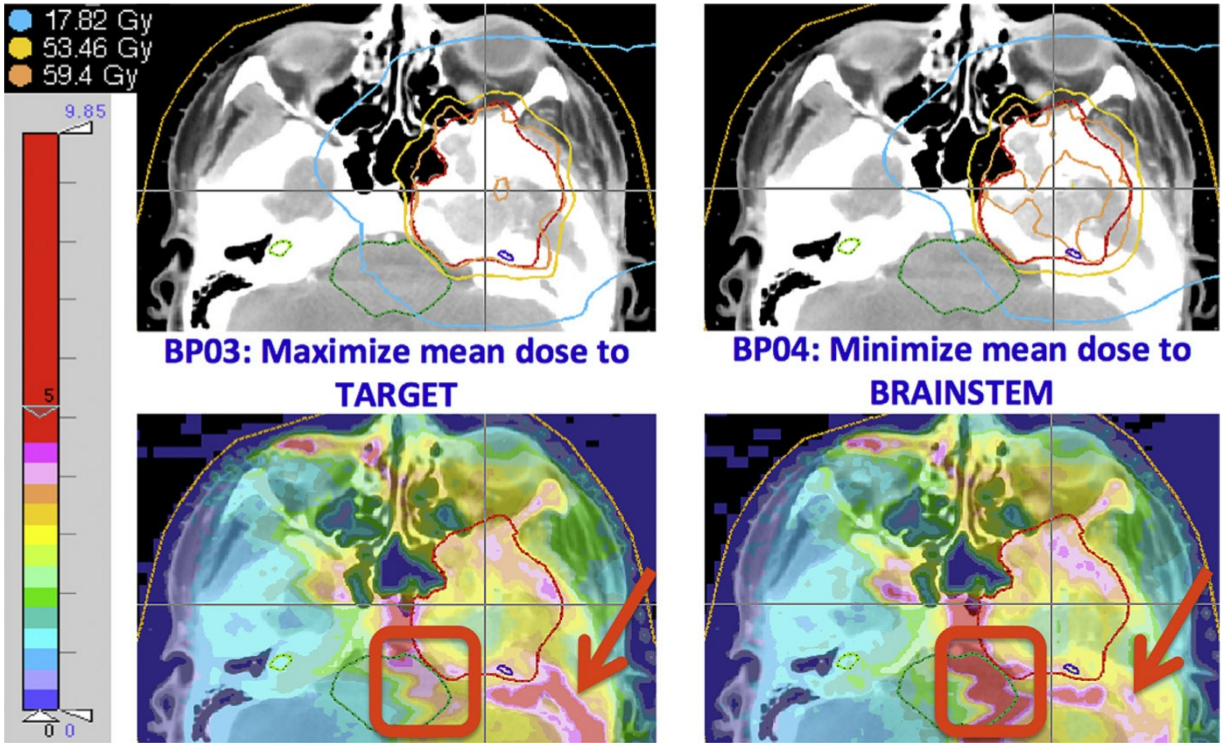
Bassler *et al.* 2014 *Acta Oncol* ***53****: 25*

The **LET-painting** (Bassler *et al.* 2014) was shown to allow modifying the **LET distribution** inside the **target** without impairing the physical dose distribution.

Optimizing the RBE-weighted dose and radiation quality in the target could **improve tumor response**.

LET-guided optimization

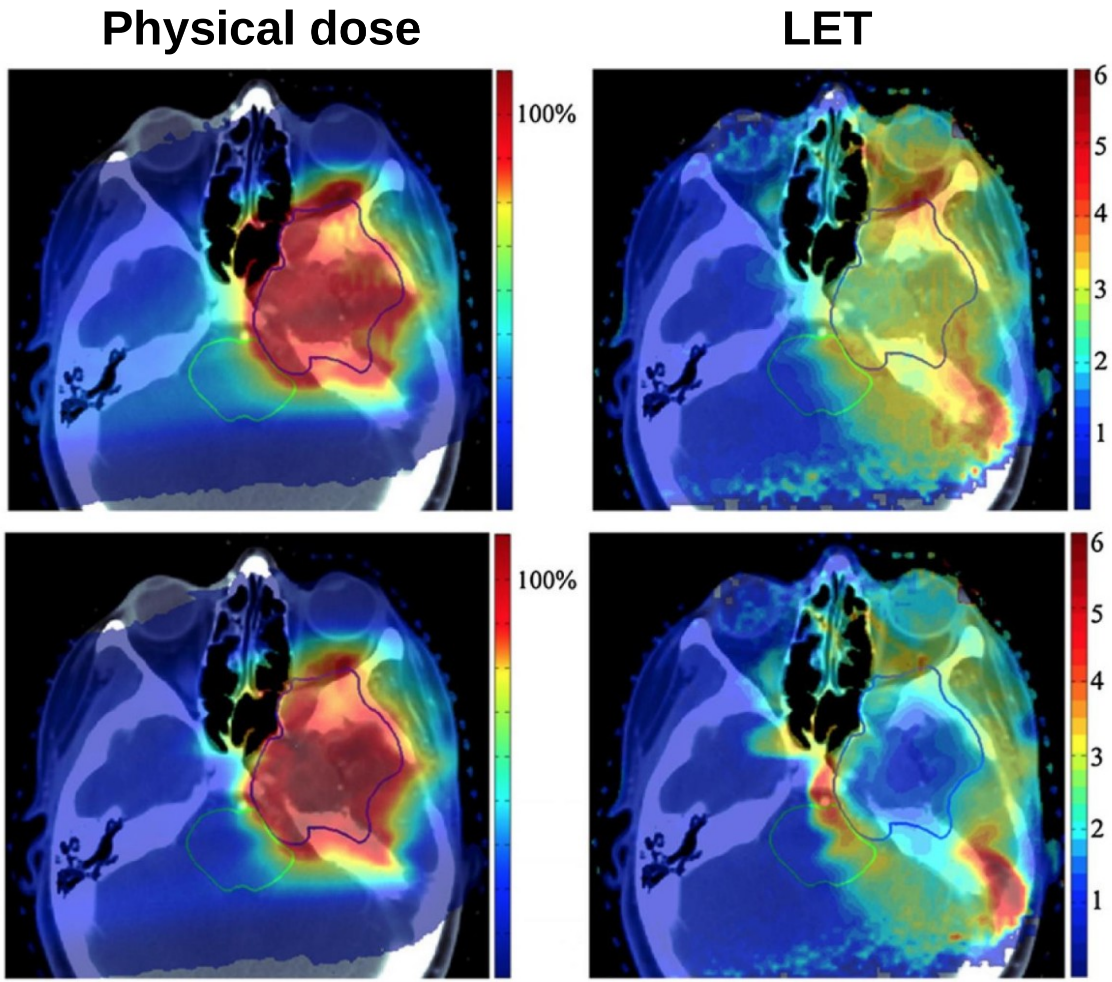
Dose and dose-average LET distributions for base plans for a case of pediatric chordoma irradiated with protons.



At a different study, Giantsoudi and co-authors have presented a LET-guided optimization approach. The results indicated that the LET distribution in the organs-at-risk could be modified at a cost on the dose distribution in the corresponding organ. A reduction of the dose to the organ-at-risk resulted in the increase of the dose-average LET.

Giantsoudi *et al.* 2013 *Int J Radiat Oncol Biol Phys* **87**:216

LET-guided optimization

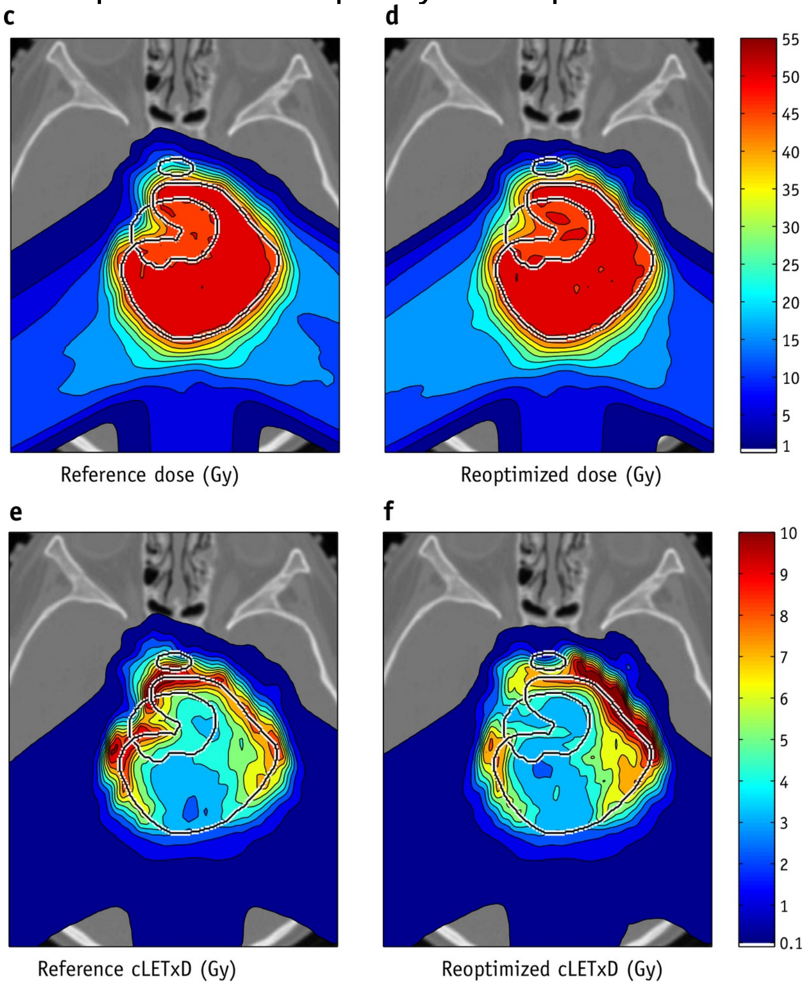

Physical dose

LET

Grassenberger et al., IJROBP 80 (5) 2011

LET-guided optimization/reoptimization

Plan comparison for a ependymoma patient irradiated with protons.

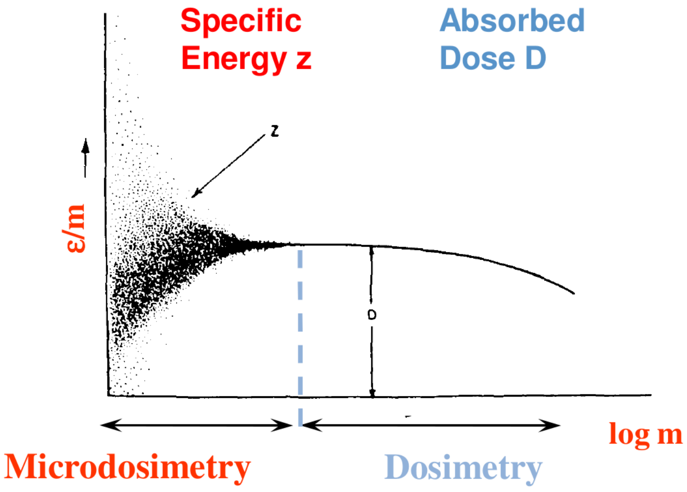


Unkelbach *et al.* 2016 *Int J Radiat Oncol Biol Phys* **96**: 1097

LET-guided optimization (Giantsoudi *et al.* 2013) and **LET-based reoptimization** (Unkelbach et al. 2016) have been successfully applied to **modify the LET distribution** in the **OARs**.

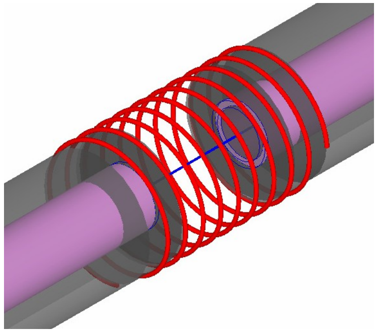
Modifying the radiation quality at critical structures could **reduce the risks of complications**.

Alternatives to LET (I): microdosimetry

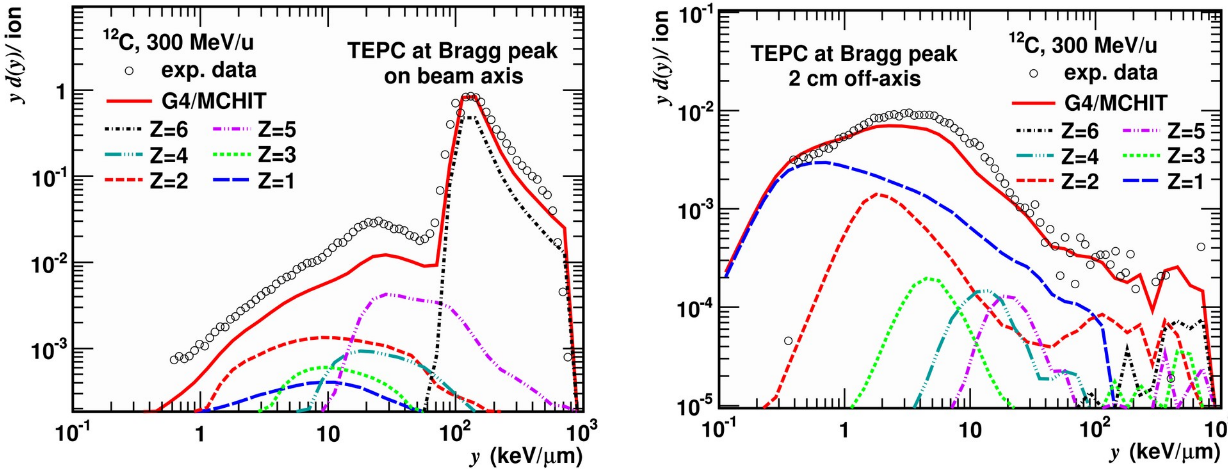


At the level of the cell nucleus (micrometer size), the energy deposition fluctuates significantly and cannot be characterized by the LET.

Microdosimetry spectra can be used to specify the radiation quality at this level. This is the base of MKM used at NIRS for the RBE modeling of carbon ions.



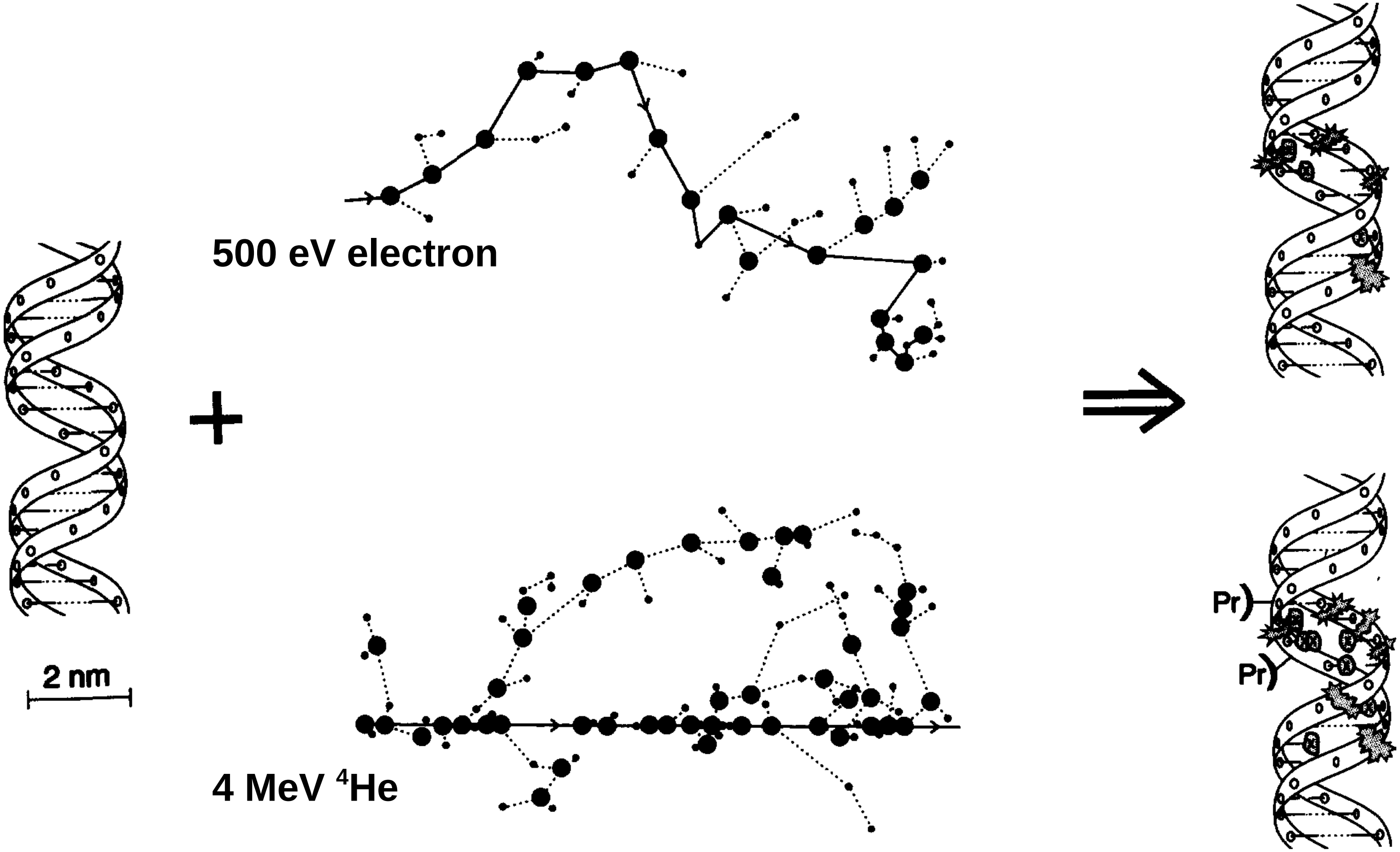
Example of tissue-equivalent proportional counter (TEPC) used in microdosimetry



Burigo *et al.* 2014 *Nucl Instr Meth Phys B* ***320***: 89

Simulation of Radiation-Induced DNA Damage

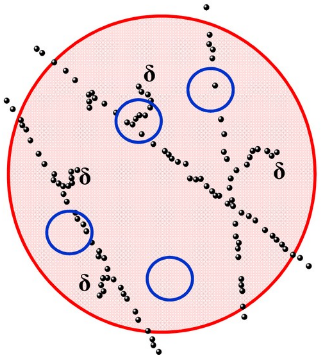
Monte Carlo simulations can be used to model the **radiation-induced DNA damages** caused by impact ionizations and radical species.



Goodhead 1994 *Int J Radiat Biol* **65** 7

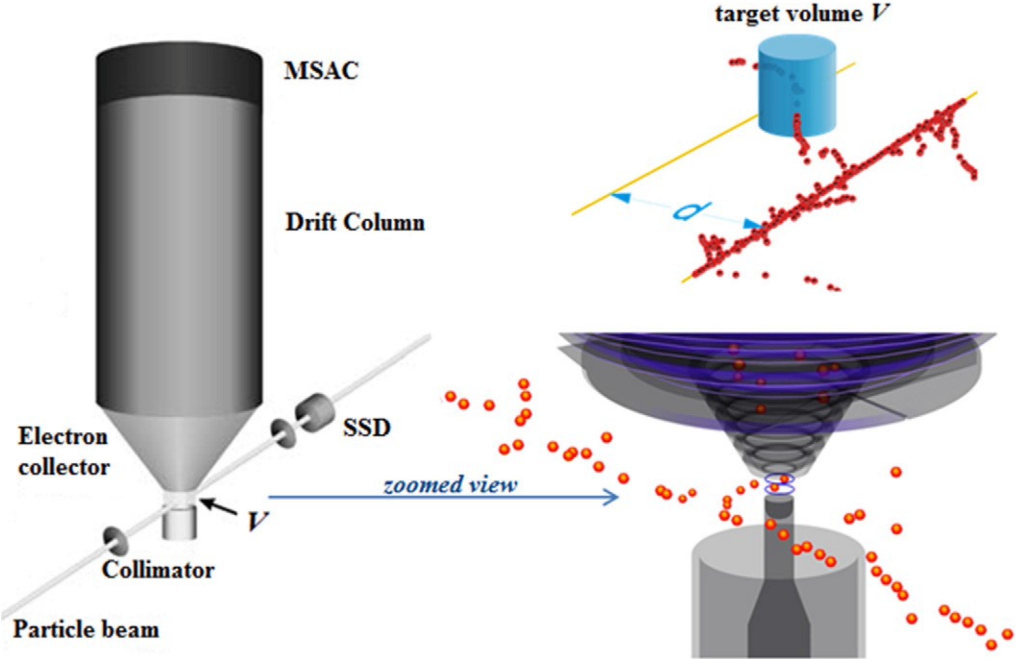
Alternatives to LET (II): nanodosimetry

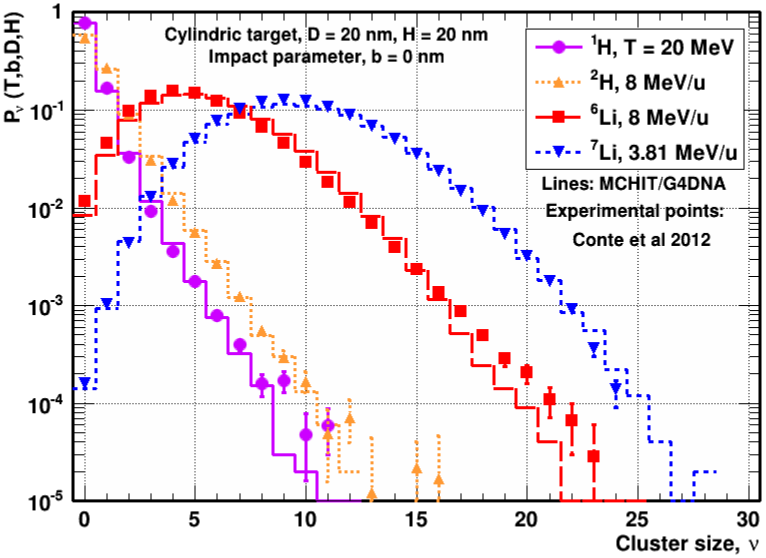
At the level of DNA structures (nanometer size), it is appropriate to specify the radiation quality by the **number of ionizations** (nanodosimetry spectrum) taking place in the volume of interest.



Ion tracks randomly crossing a cell nucleus.

Electron-counting nanodosimeter





Burigo *et al.* 2016 *Phys Med Biol* ***61***: 3698

Take home message: Why Monte Carlo in Medical Physics?

In Physics: **More accurate transport of particles in the medium**

- More accurate modelling of dose deposition (**dosimetry**)
- Better understanding of spectrum effects in dosimetry and **imaging**

In Biology: Better understanding of radiation induced DNA damage

- Accurate dosimetry allows better biological understanding of radiation effects
- Better understanding of particles interacting with DNA

In Oncology: Improvements in physics and biology means improvements in cancer survival rates

- Targeted radiotherapy needs both physics and biology to work together in order to accurately target the tumor.

By courtesy of João Seco

Thank you for your attention!