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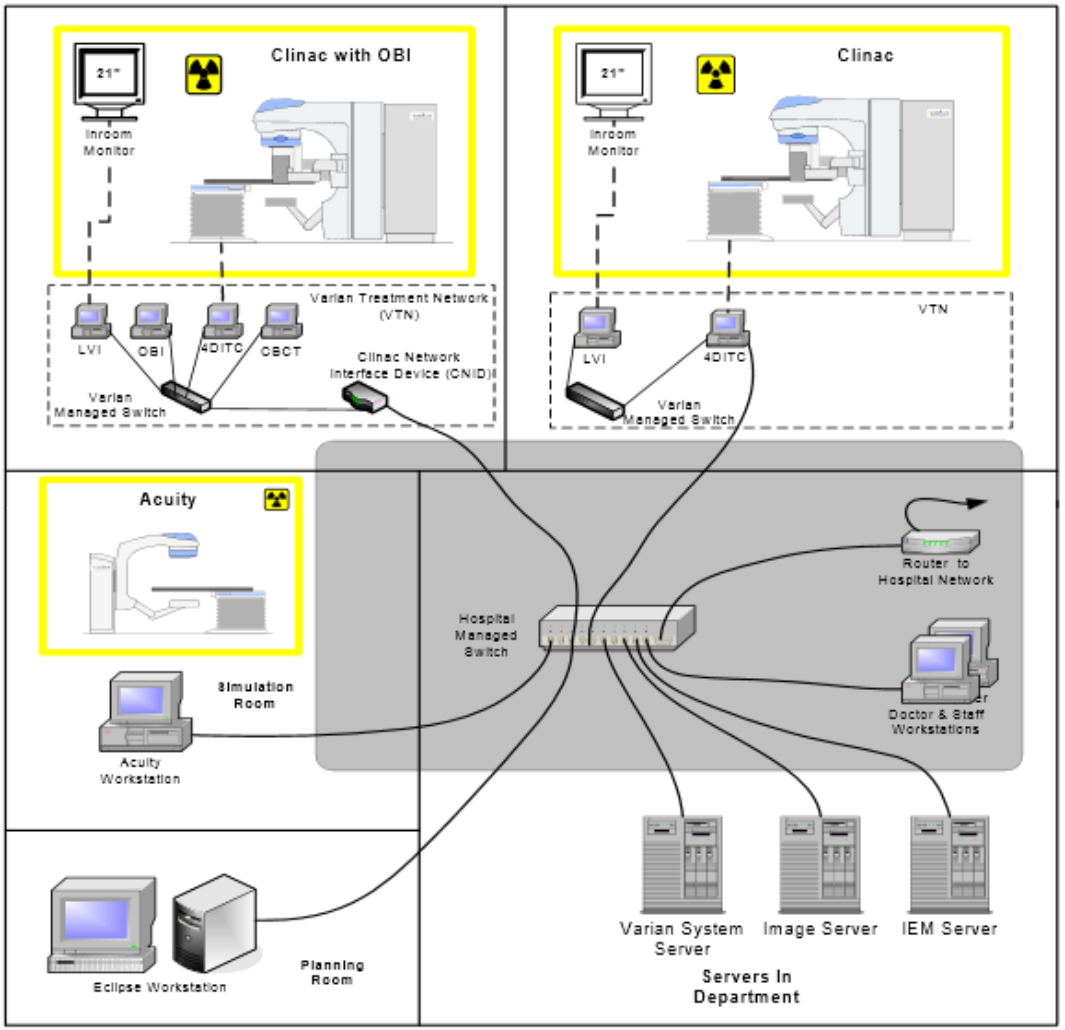
Computerized treatment planning systems - II

CRISTER CEBERG

Modern computerized treatment planning



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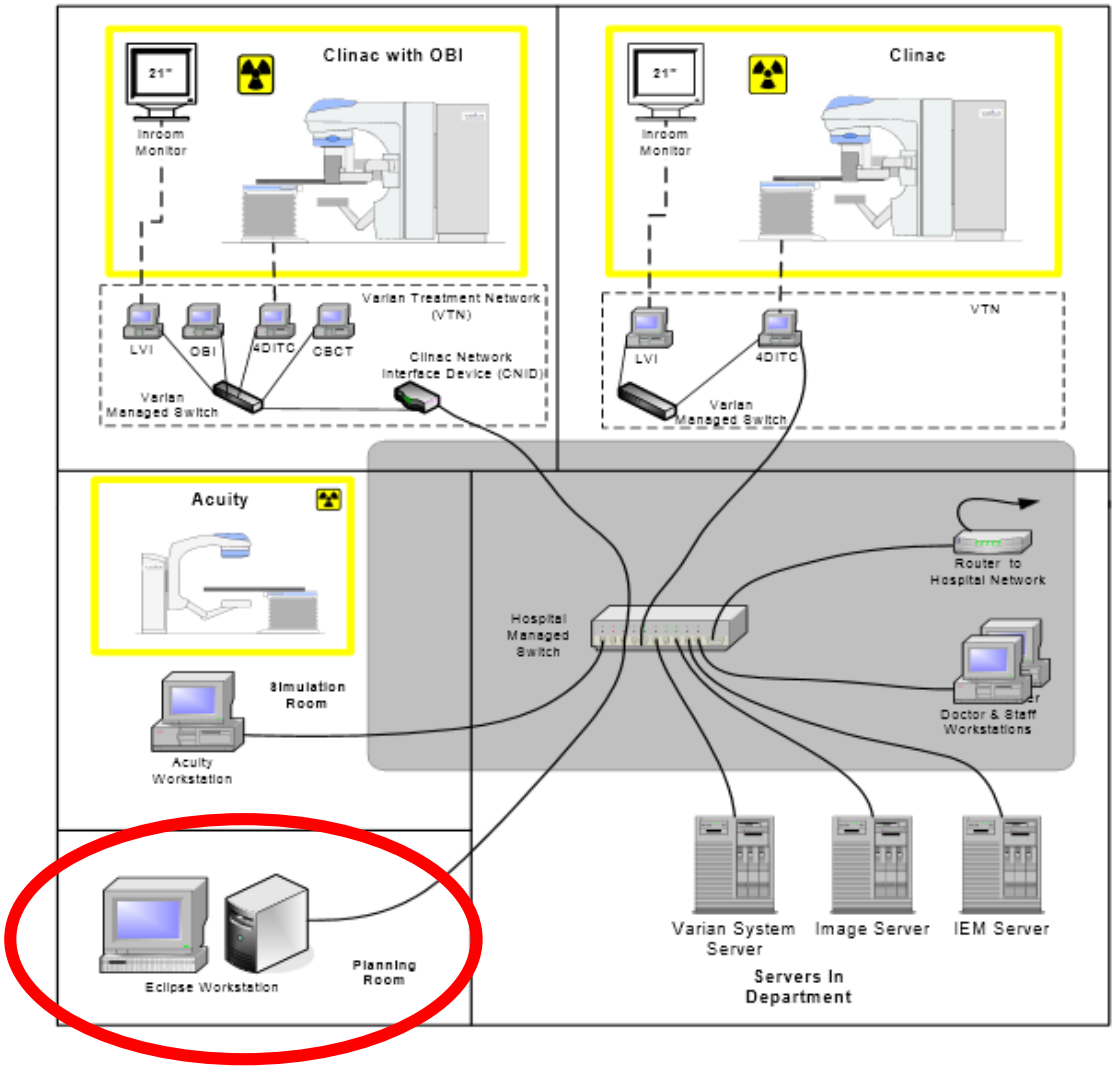
Modern computerized treatment planning



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Generally available hardware

» Network solutions

- Servers
- Workstations
- Citrix clients

Dell Precision T5400/T5500

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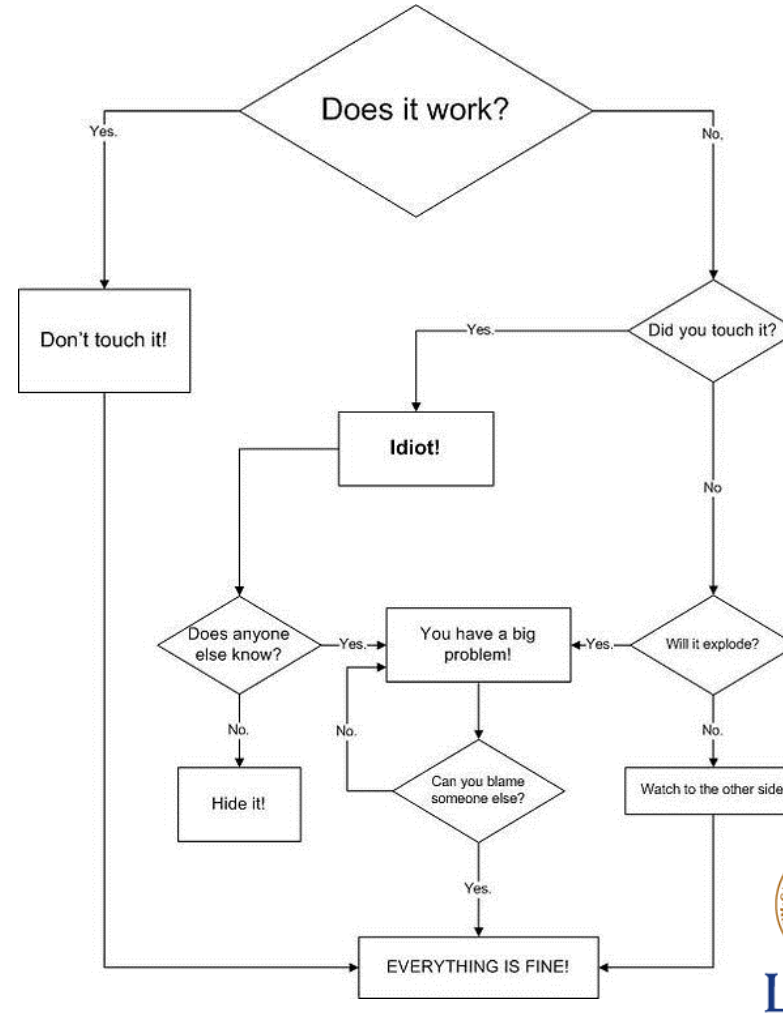
...not so accessible software

- Documentation
  - Scientific papers
  - Reference manuals
- The implementation is still often a ”black box”!
- We will look at general features and examples



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Types of dose calculation algorithms

	Data required
Based on measured data	Large amounts of measured data are entered directly into the TPS and reproduced by the algorithm; depth dose profile data may be entered directly into the TPS
Analytical functions	Analytical functions model the physics, but the parameters for the functions are usually fitted using measured data The tissue air ratio–scatter air ratio (TAR–SAR) separation of primary and scatter components could be considered, as well as a superposition of differential elements
Superposition of differential elements	Algorithm integrates over differential dose elements; spectral data and some representation of the photon fluence are required, but limited other parameters are needed
Monte Carlo based models	Virtually all input data are the basic physics of interactions, and include very little measured data; however, most Monte Carlo methods involve modelling of the machine collimation system and radiation sources, etc.

IAEA TRS 430

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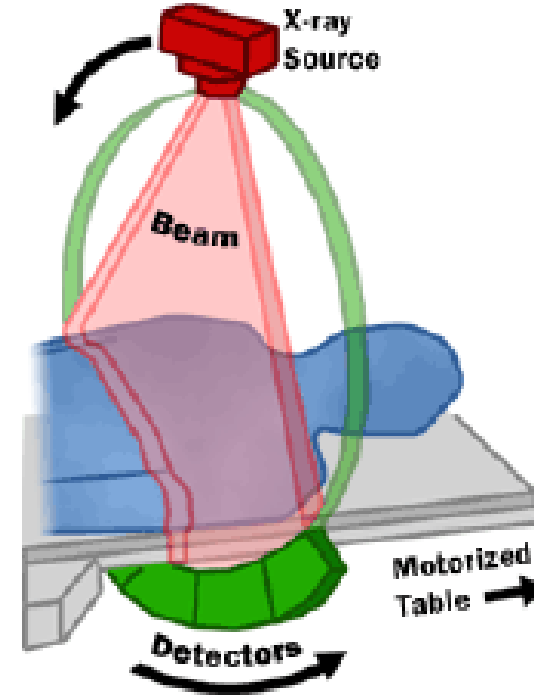
CT for patient information

- Diagnostic tools
- Target determination
- Basis for calculations
  - Hounsfield units

$$HU = 1000 \times \frac{\mu - \mu_{H_2O}}{\mu_{H_2O}}$$



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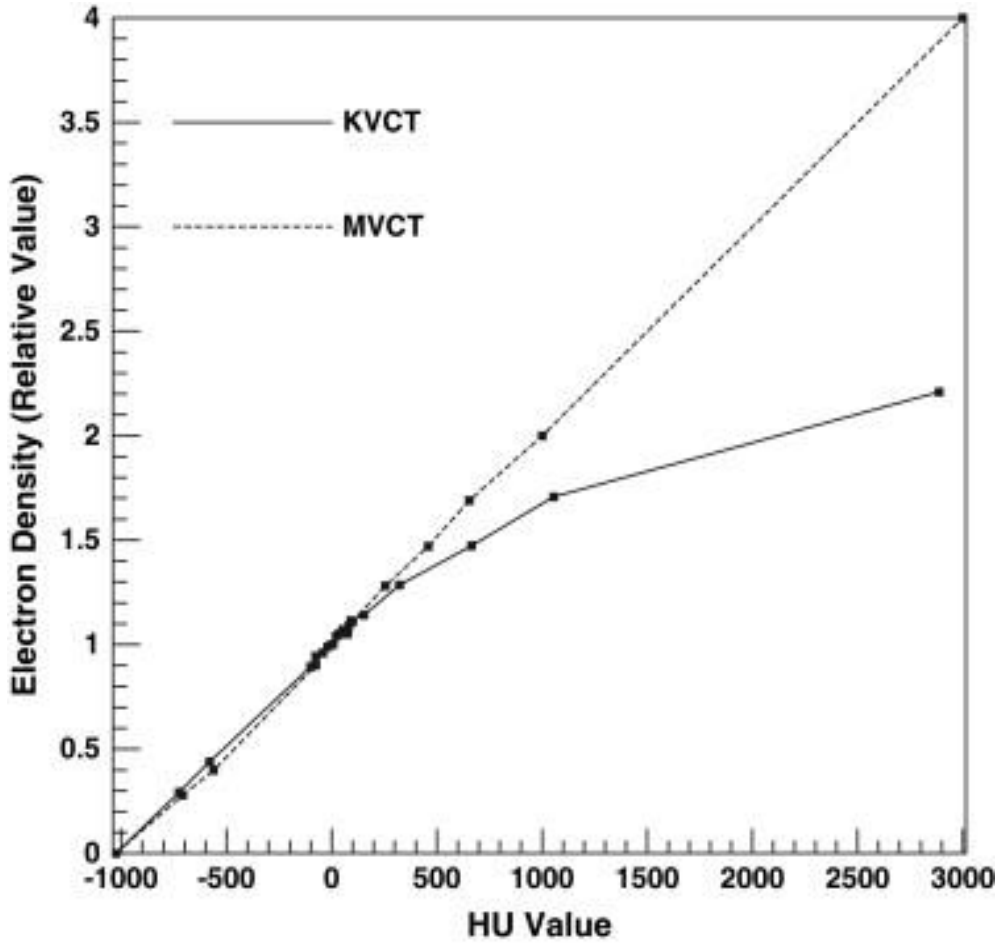
Conversion to electron density



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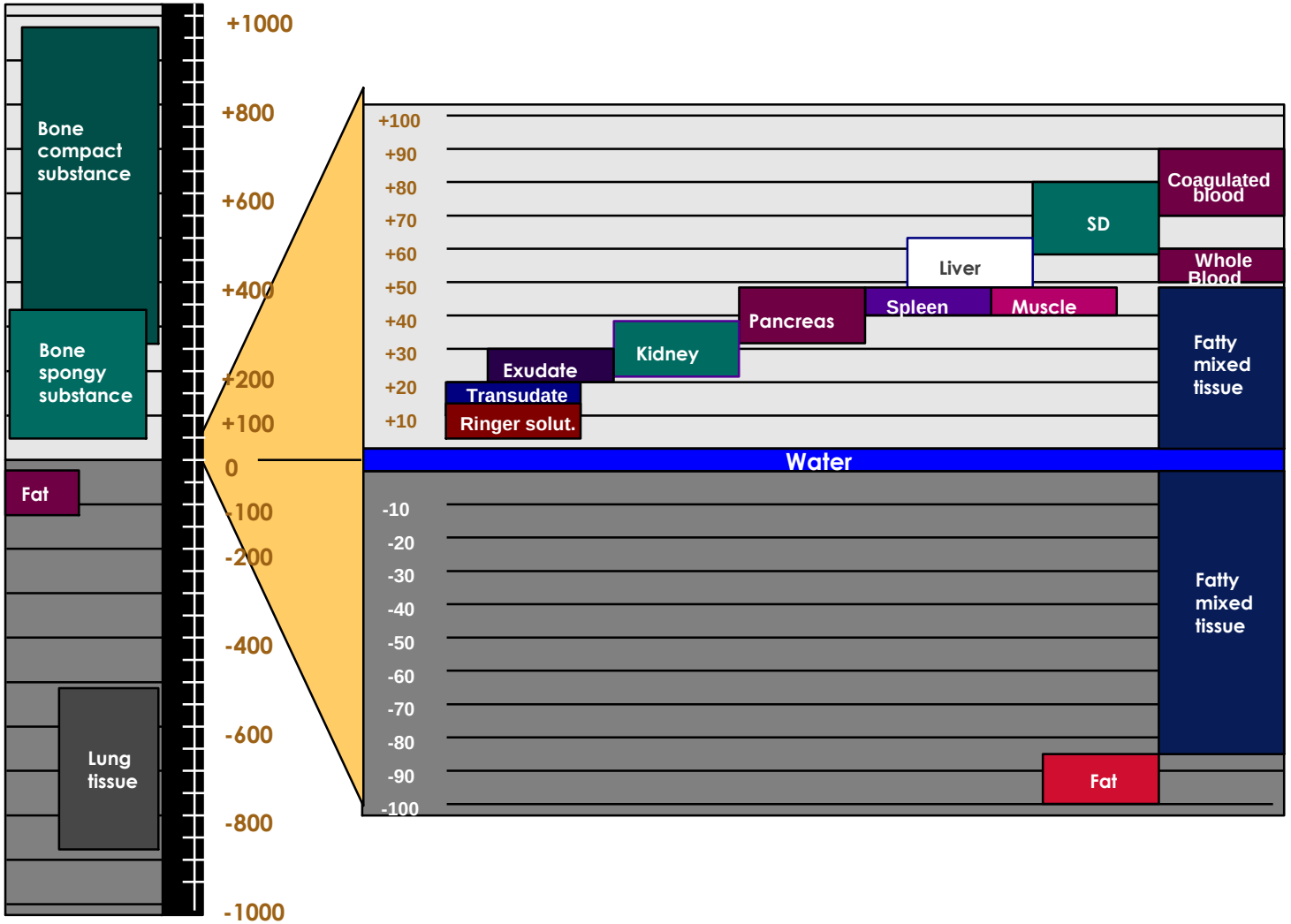
The Hounsfield scale



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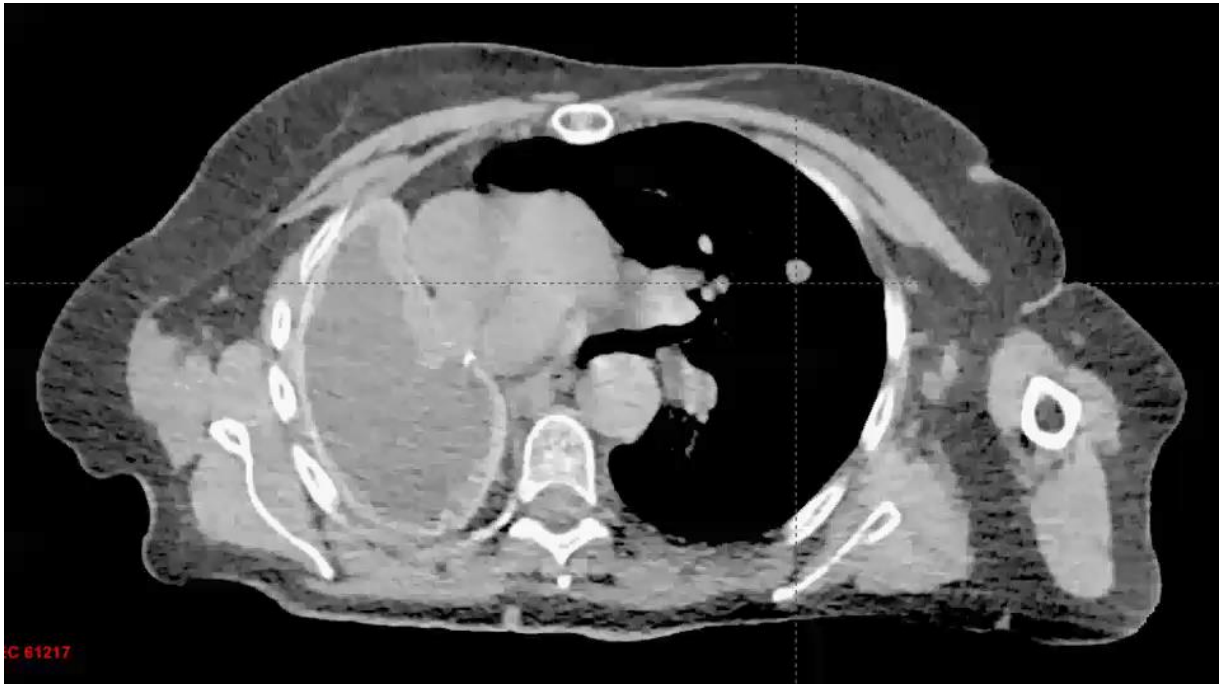
Patients in motion



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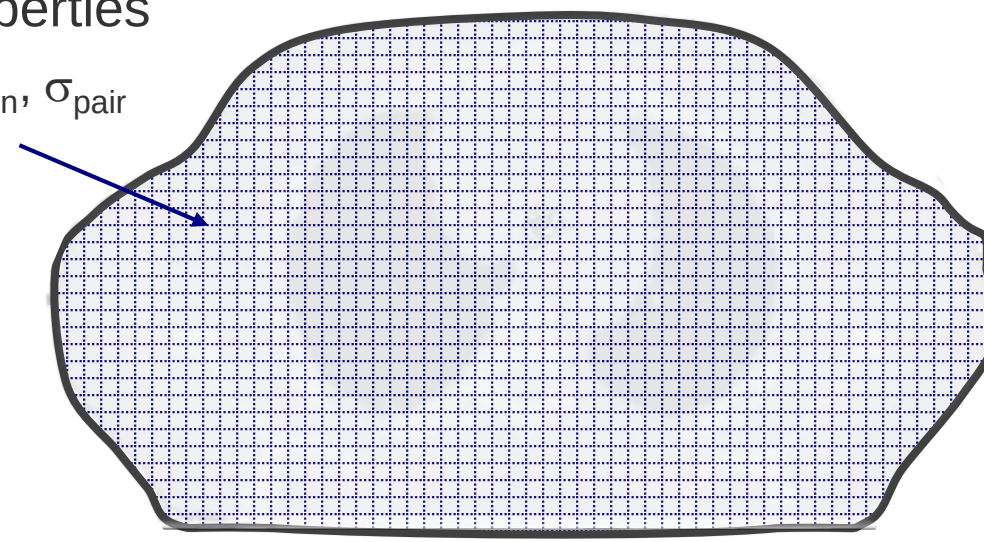
Creating a voxel matrix

- Map to each voxel
  - Tissue type
  - Composition and density
  - Interaction properties
    - σ_{photo}, $\sigma_{compton}$, σ_{pair}



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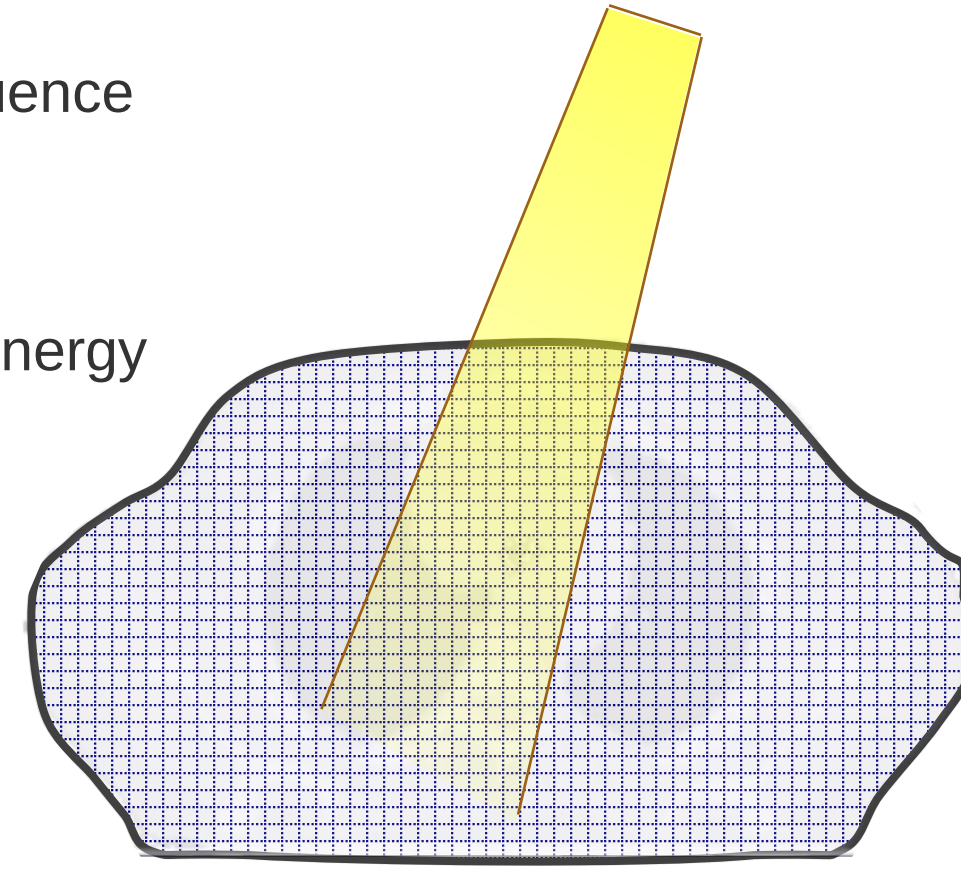
General components of calculation models

» Incident photon fluence

» Raytracing

» Redistribution of energy



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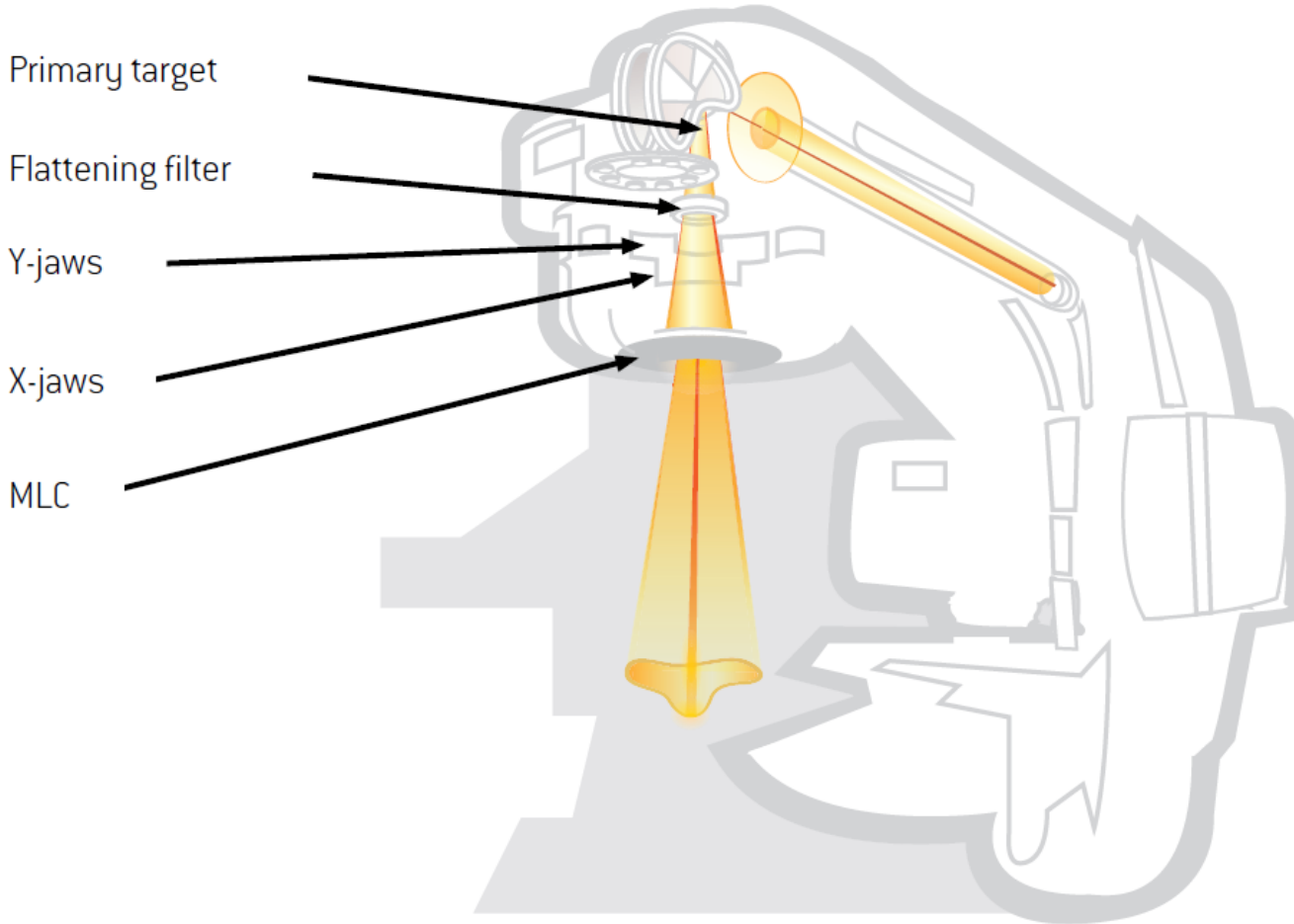
Incident fluence



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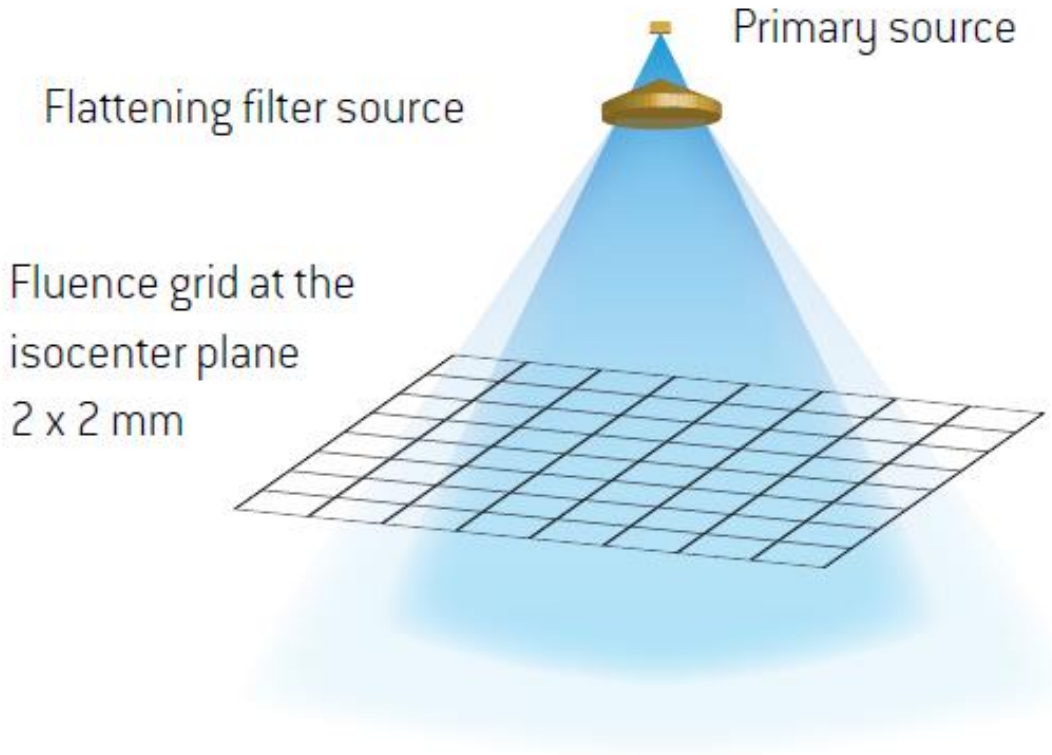
Primary and secondary sources



RayStation

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Primary source

Beam profile | **Gaussian primary source** | **Incident primary profile**

(can also be a wedge profile)

Profile slope and source width are fitting parameters

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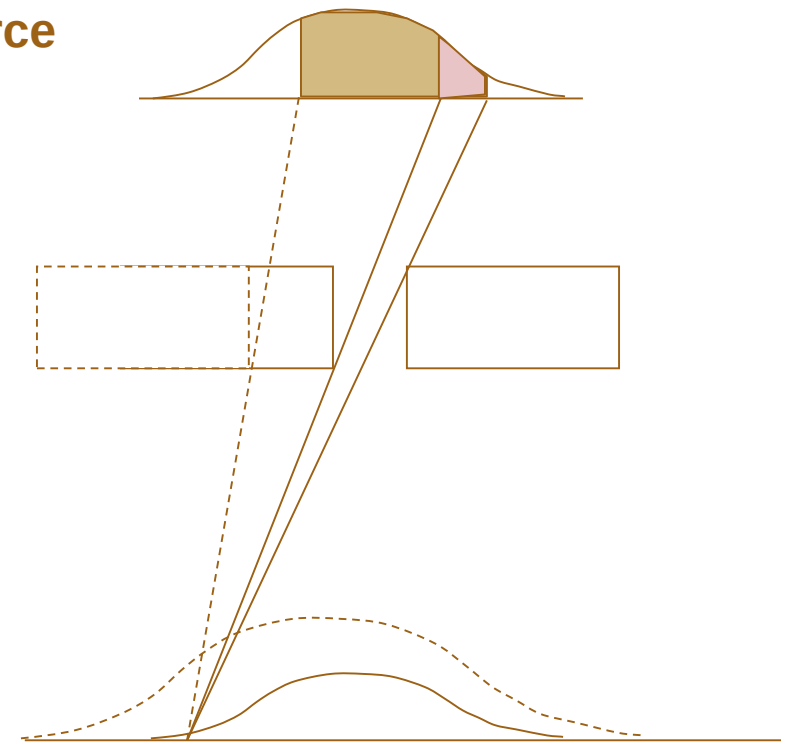
Flattening filter source

Gaussian secondary source

Calc point's view

Head scatter contribution



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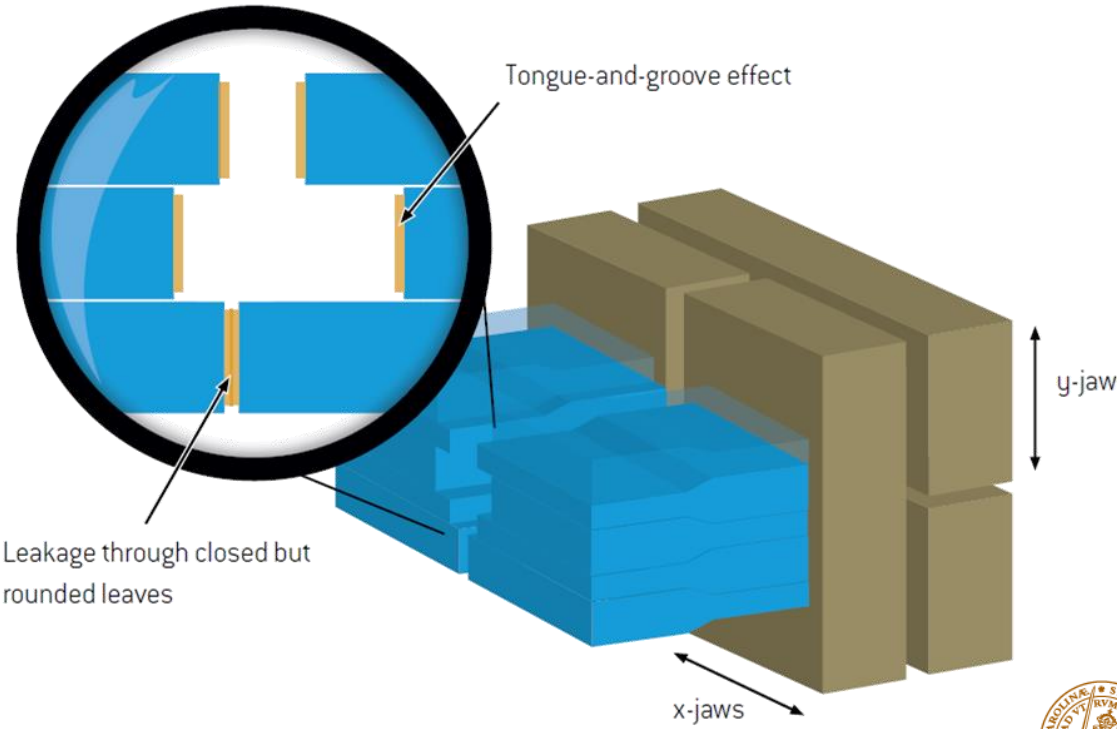
Collimator scatter source

» Transmission and leakage

» Scatter from visible surfaces



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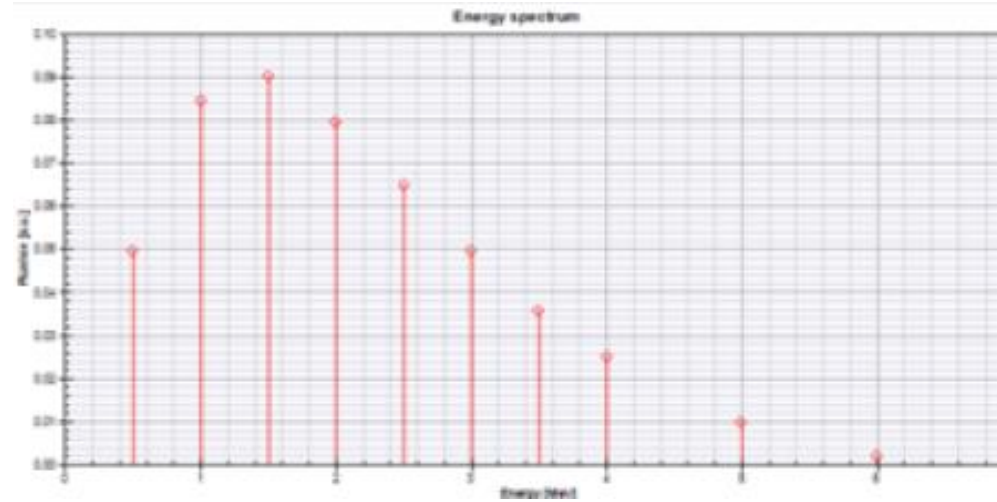
Incident photon fluence

» The total incident photon fluence

- Primary source
- Flattening filter
- Collimator scatter

» Spectrum $\Psi_0(E_i)$



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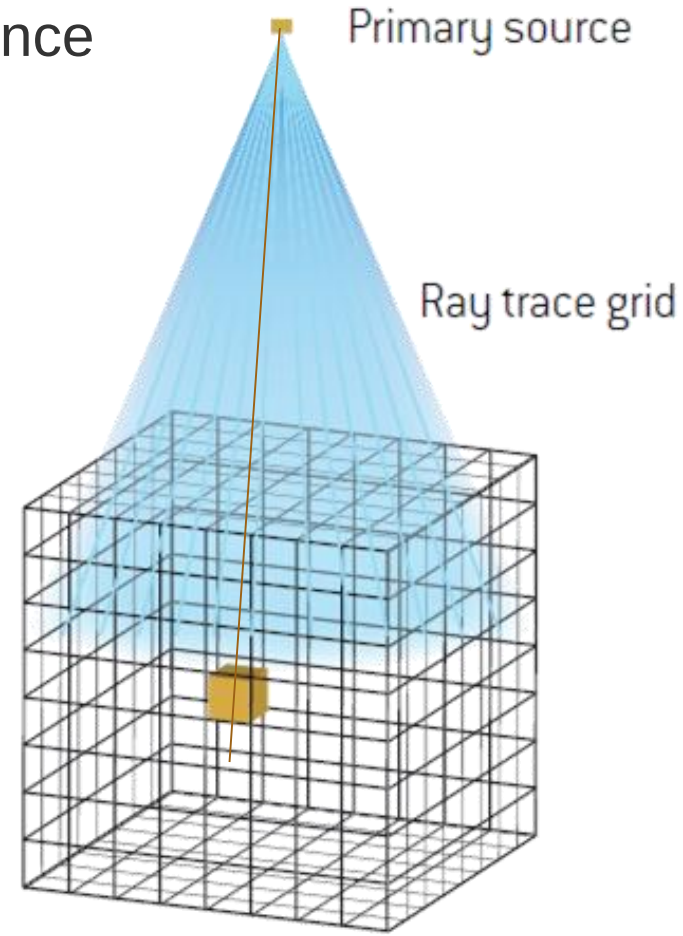
Incident photon fluence

» The total incident photon fluence
  – Primary source
  – Flattening filter
  – Collimator scatter

» Raytracing through density matrix



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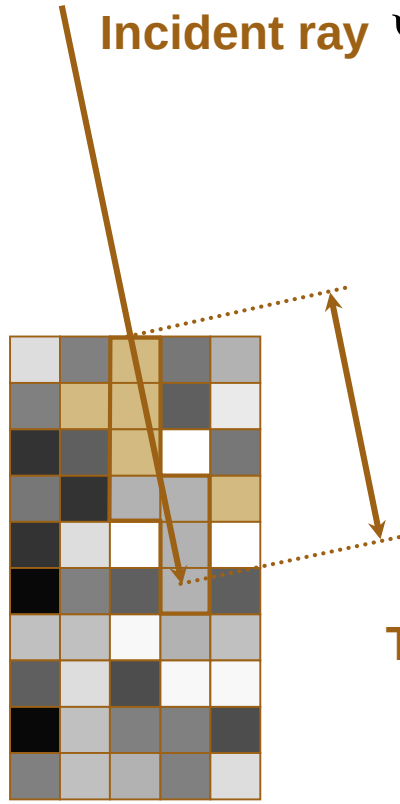
Raytracing



Incident ray $\Psi_0(E_i)$

Attenuation

$$\Psi(\bar{r},E_i) = \Psi_0(E_i)\exp\left[-\int_{\bar{r}_0}^{\bar{r}} \mu(\bar{r}',E_i)dl\right]$$

Total energy released in matter (TERMA)

$$T(\bar{r}) = \int_E \frac{\mu(\bar{r},E')}{\rho_m(\bar{r})}\Psi(\bar{r},E')dE$$

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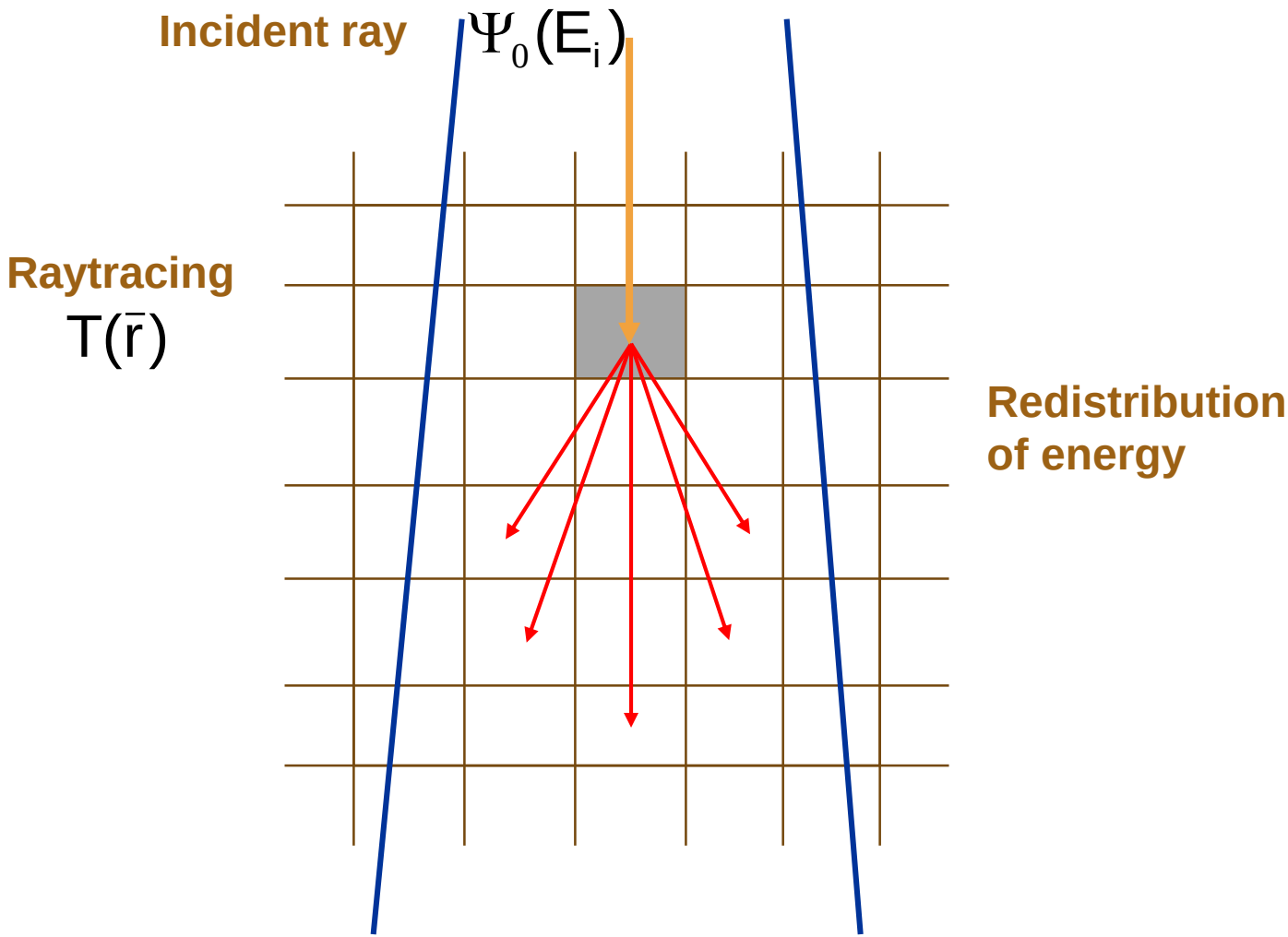
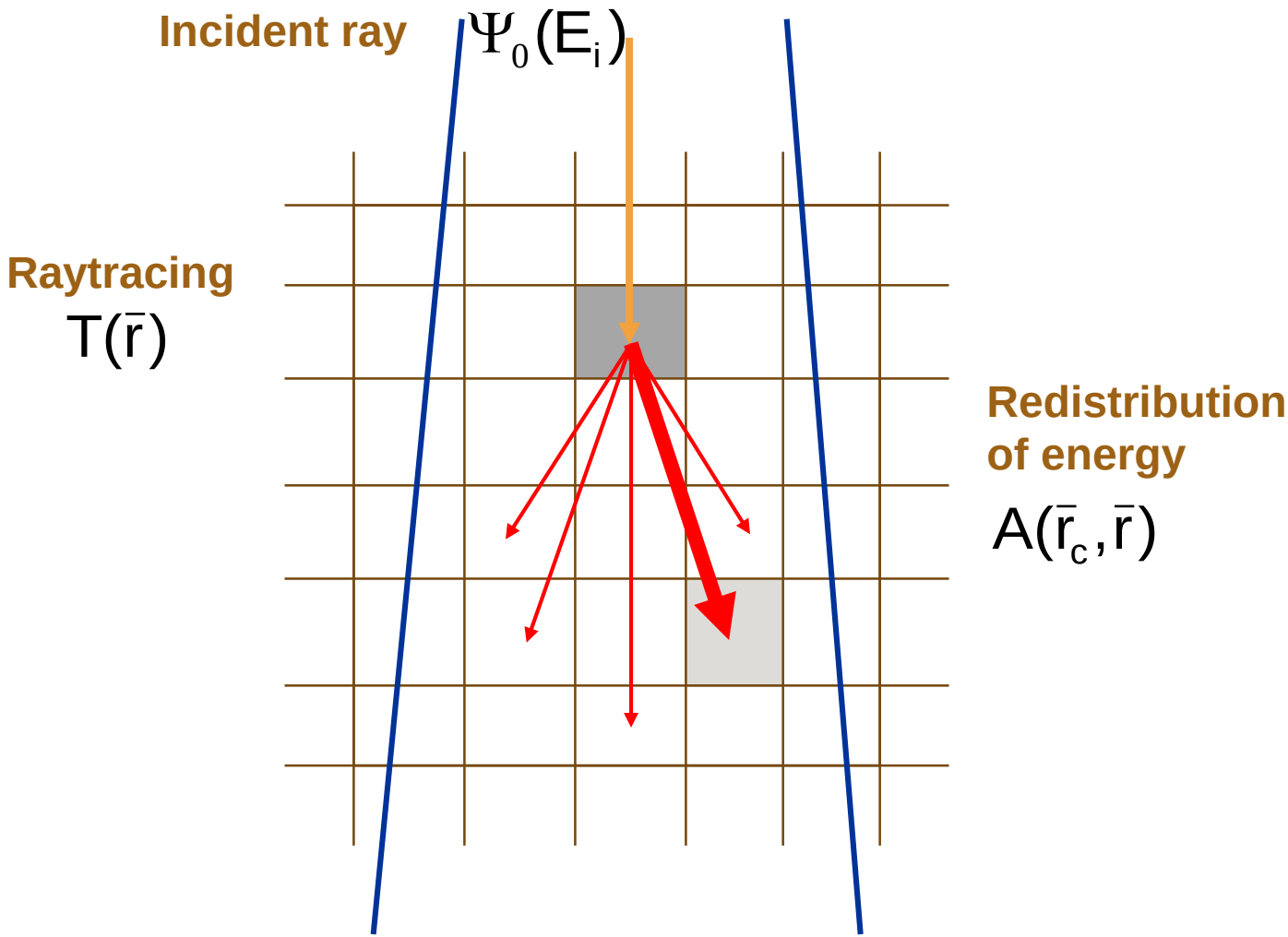
Redistribution of energy



Kernel


Incident ray
$\Psi_0(E_i)$
Raytracing
$T(\bar{r})$
Redistribution of energy
$A(\bar{r}_c, \bar{r})$

Monte Carlo calculated kernels

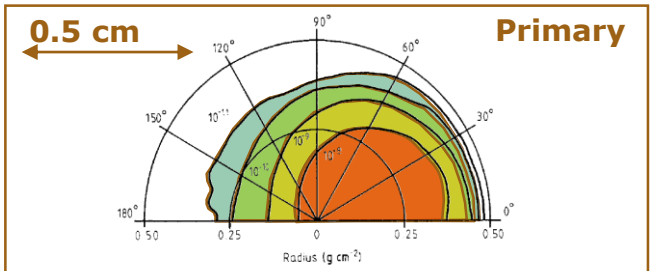


Figure 4. Primary energy deposition kernel in isoline format for 1.25 MeV photons. The units are cGy MeV^{-1} photon^{-1}.

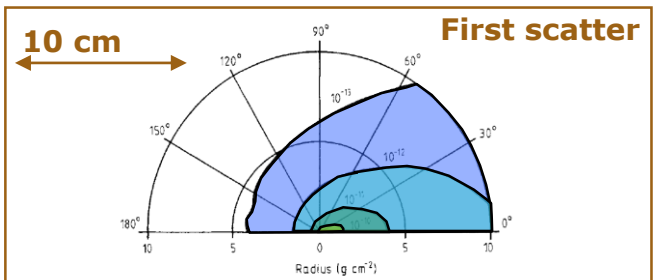


Figure 5. First scatter energy deposition kernel in isoline format for 1.25 MeV photons. The units are cGy MeV^{-1} photon^{-1}.

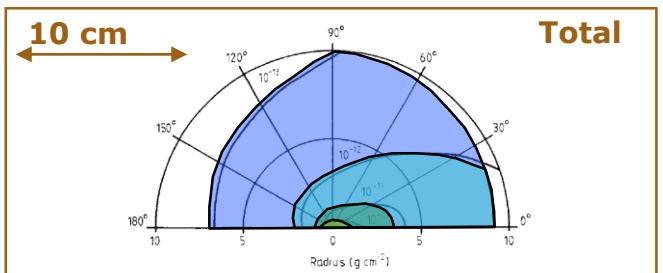
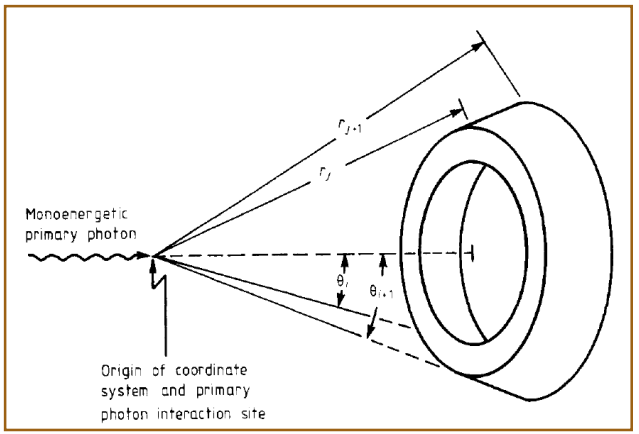


Figure 6. Total energy deposition kernel in isoline format for 1.25 MeV photons. The total energy deposition kernel is the sum of all the energy deposition kernel components. The units are cGy MeV^{-1} photon^{-1}.

» Absorbed dose distribution around a single interaction point

» Example for 1.25 MeV



Mackie et al, Phys Med Biol 33:1-20, 1988

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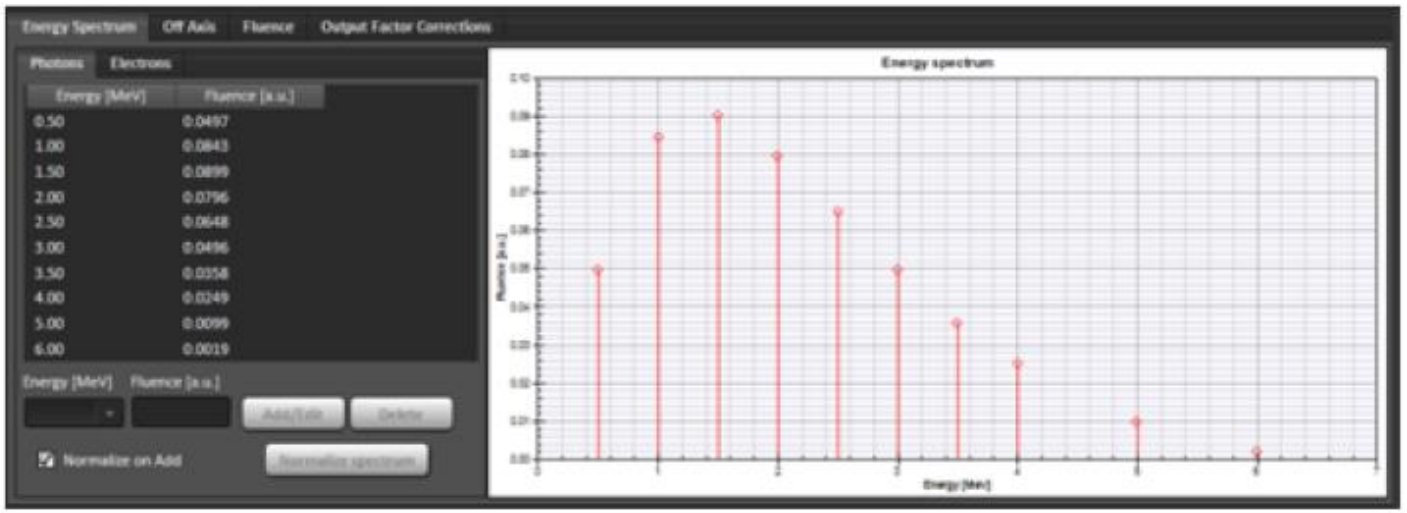
Monte Carlo calculated kernels

» Library of mono-energetic kernels

» Estimate of linac spectrum (fitting parameter)

» Composite poly-energetic kernel is obtained by summation



RayStation

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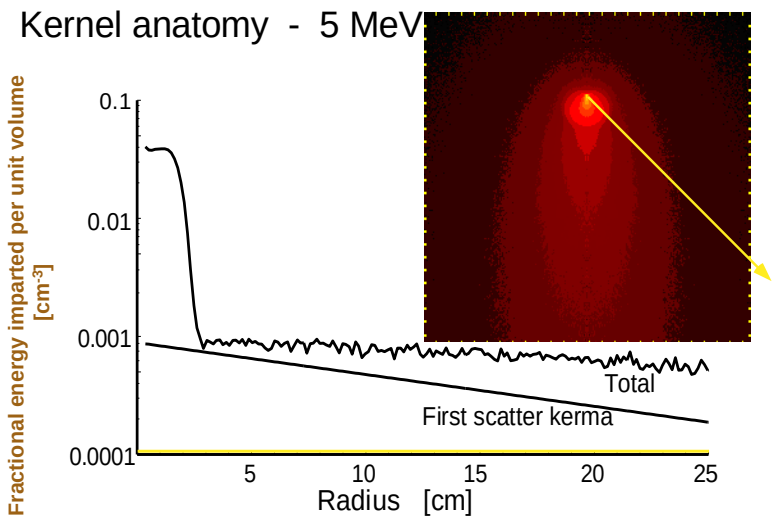
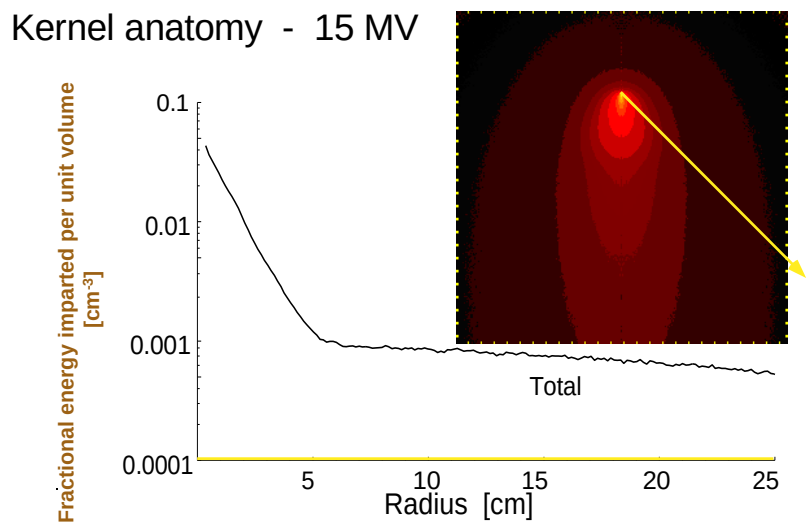
Monte Carlo calculated kernels





$$A(r) = \frac{c_1 \cdot e^{-ar}}{r^2} + \frac{c_2 \cdot e^{-br}}{r^2}$$

Ahnesjö, Med Phys 16:577-592, 1989

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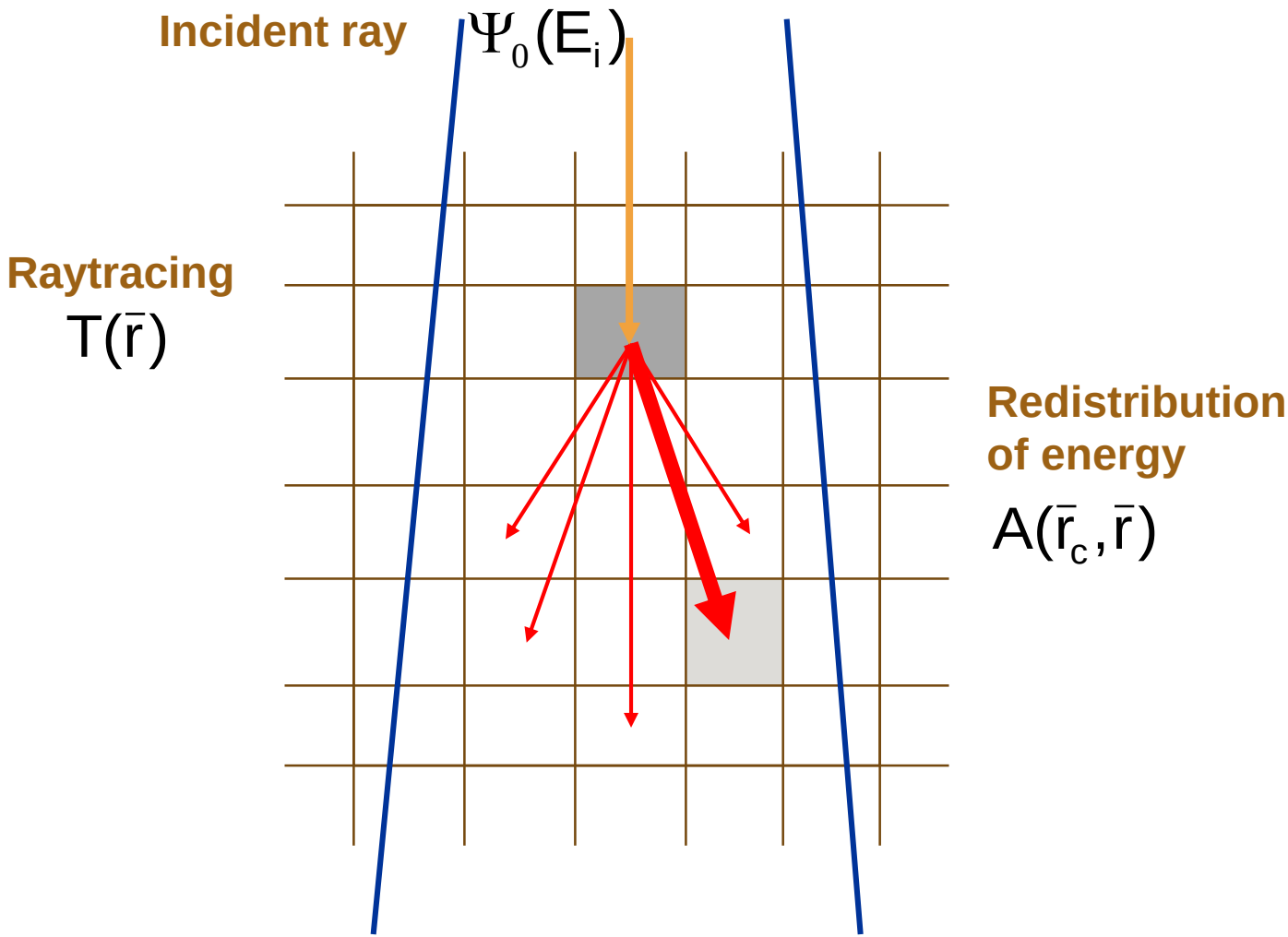
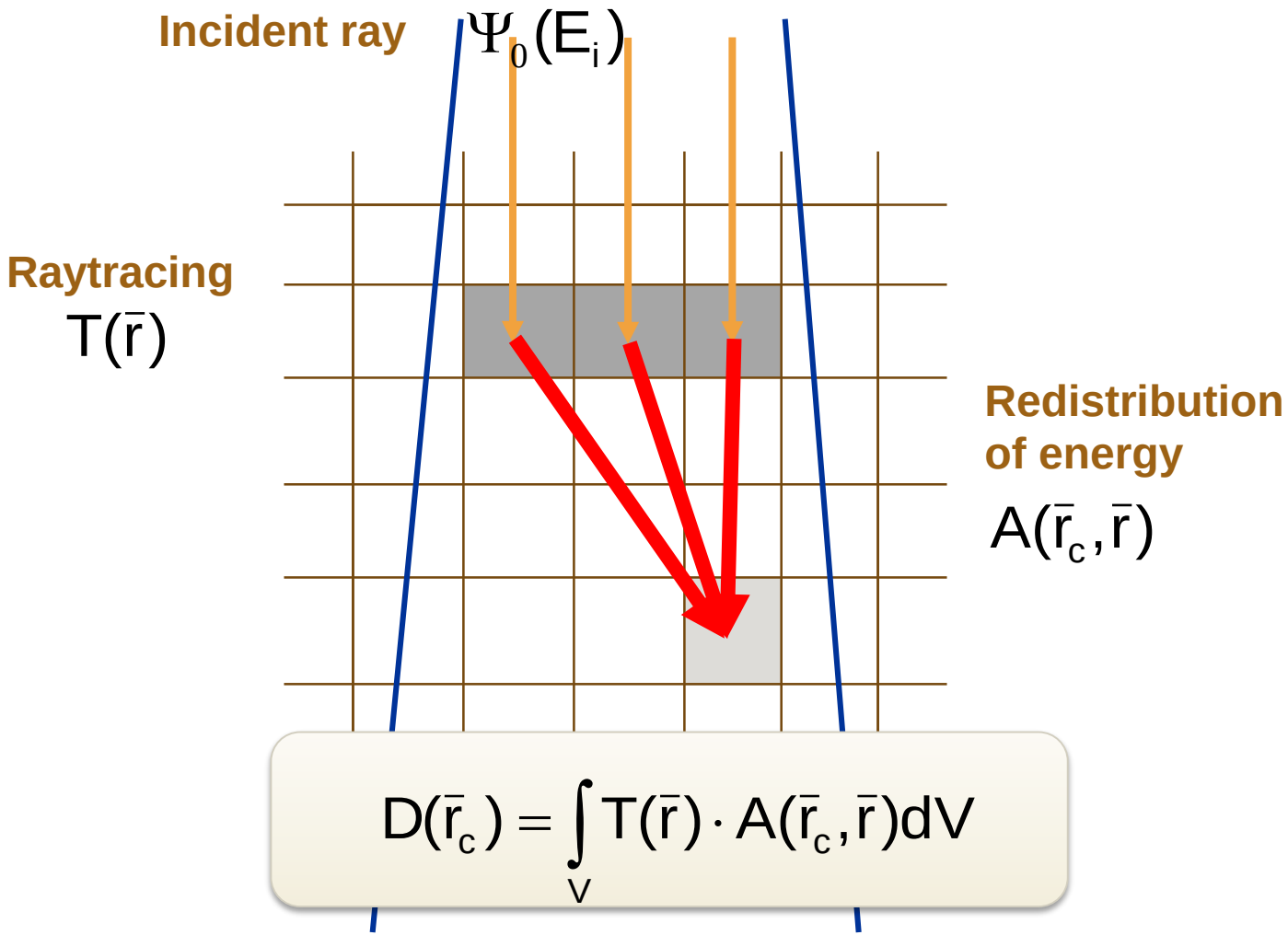
Kernel


Incident ray
$\Psi_0(E_i)$
Raytracing
$T(\bar{r})$
Redistribution of energy
$A(\bar{r}_c, \bar{r})$

Kernel integration



$$D(\bar{r}_c) = \int_V T(\bar{r}) \cdot A(\bar{r}_c, \bar{r}) dV$$

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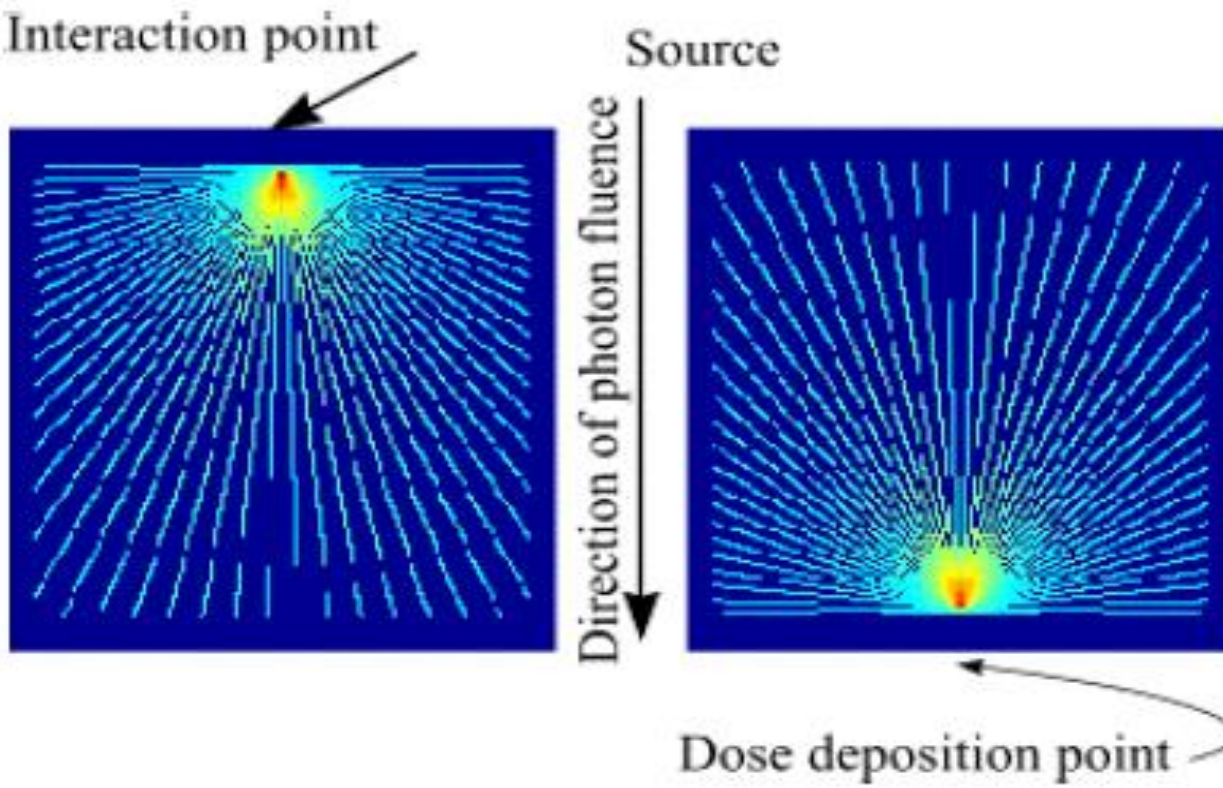
Kernel integration

» Interaction *vs.* deposition point-of-view



Kernel integration

$$D(\bar{r}_c) = \int_V T(\bar{r}) \cdot A(\bar{r}_c, \bar{r}) dV$$

» Convolution

– Invariant kernel

– $D(\bar{r}_c) = T(\bar{r}) \otimes A(\bar{r}_c, \bar{r}) = FFT^{-1}\left[FFT(T) \cdot FFT(A)\right]$

» Superposition

– Variation of energy, divergence, density

– $D(\bar{r}_c) = \sum T(\bar{r}) \cdot A(\bar{r}_c, \bar{r})$

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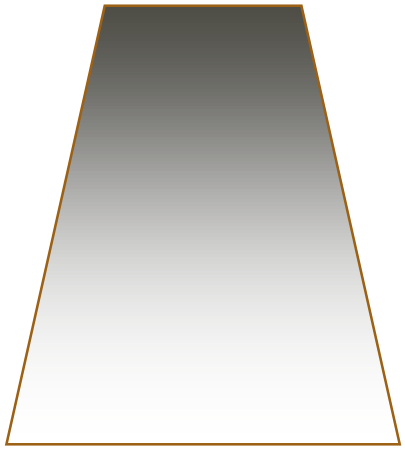
Convolution (2D)



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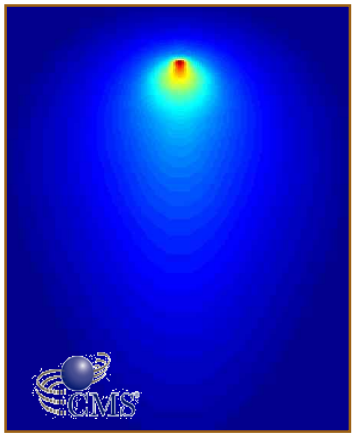

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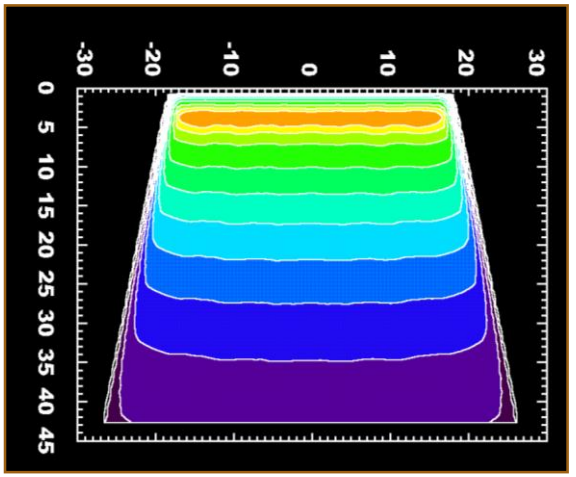

TERMA ⊗ **Dose Deposition Kernel** = **Absorbed Dose**

Tommy Knöös

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Example – XiO FFT

- Poly-energetic kernels are obtained from Mackie's kernel library, re-sampled to Cartesian coordinates
- Separate kernels for primary and scatter dose
  - Primary part integrated with high resolution in small volume
  - Scatter part with lower resolution over larger volume
- FFT-based convolution
  - Large time saving (65%)
  - Effects of invariant kernel

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Limitations

» Kernels are not invariant

- Energy distribution varies with position (beam hardening and beam softening)
- Divergence
- Density variations

» Approximations are needed

- FFT convolution requires invariant kernels
- Analytical methods are time consuming

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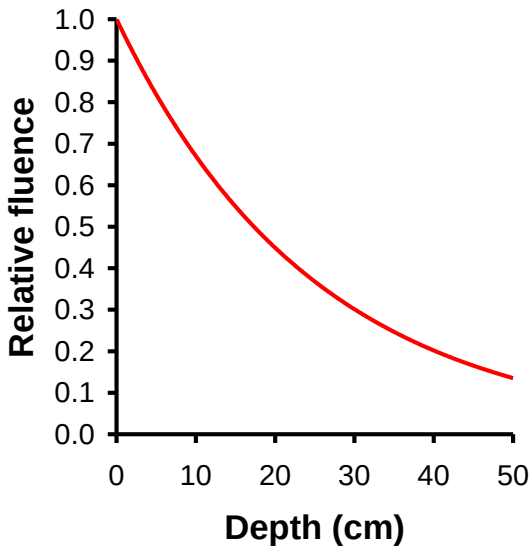
Pencil-beam approximation

» Pre-convolving depth dimension



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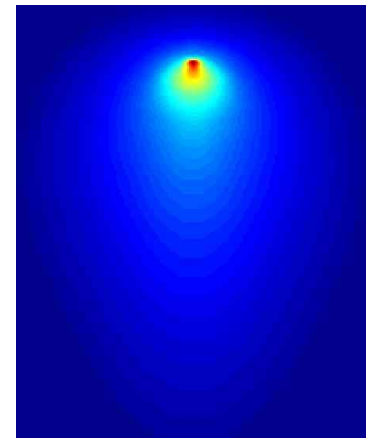

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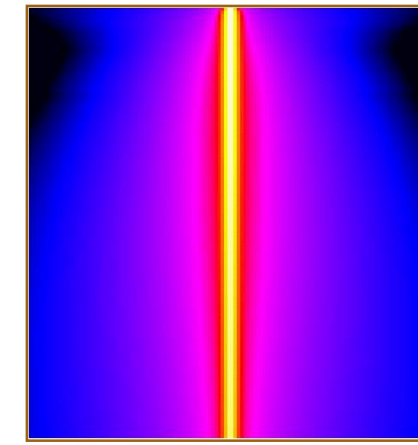
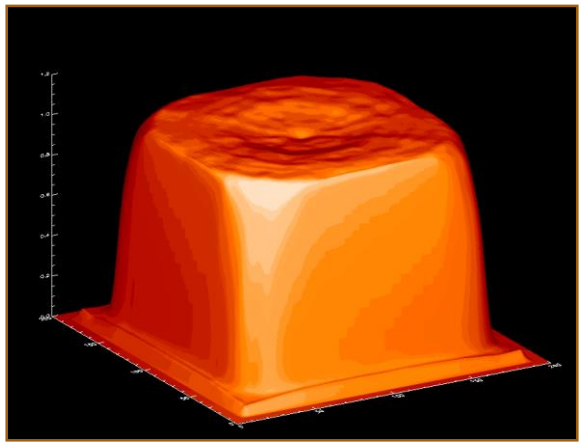


Tommy Knöös

Pencil-beam approximation

» Reduce calculation from 3D -> 2D => faster



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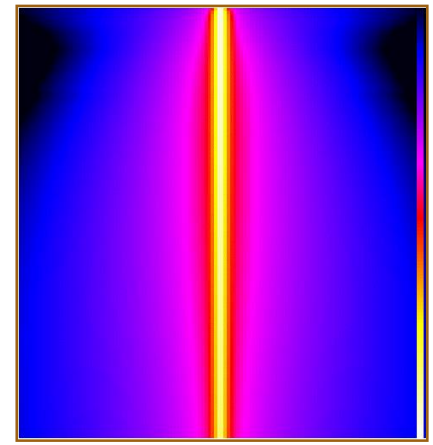

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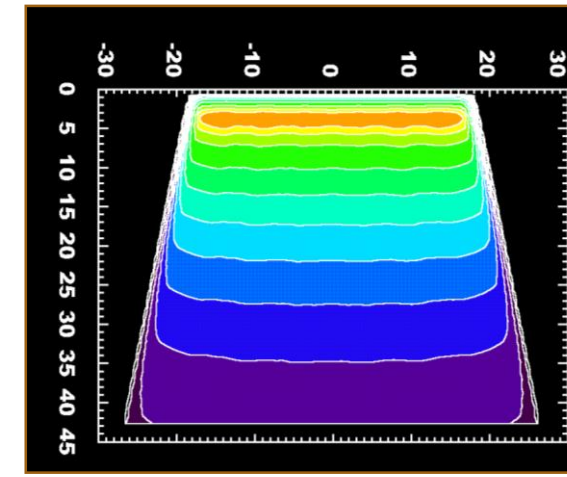

Energy fluence ⊗ **Dose Deposition Kernel** = **Absorbed Dose**

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Pencil-beam kernels

» Monte Carlo calculations (standard)

Use of fast Fourier transforms in calculating dose distributions for irregularly shaped fields for three-dimensional treatment planning[a)]

Radhe Mohan and Chen-Shou Chui
Department of Medical Physics, Memorial Sloan–Kettering Cancer Center, New York, New York 10021

(Received 30 June 1986; accepted for publication 22 October 1986)

A pencil beam model for photon dose calculation

Anders Ahnesjö
Department of Radiation Physics, Karolinska Institute, Stockholm, Sweden and Helax AB, Box 1704, S-751 47 Uppsala, Sweden

Mikael Saxner and Avo Trepp
Helax AB, Box 1704, S-751 47 Uppsala, Sweden

(Received 29 October 1990; accepted for publication 1 July 1991)

» Extracted from measurements

Extraction of pencil beam kernels by the deconvolution method

Chen-Shou Chui and Radhe Mohan
Department of Medical Physics, Memorial Sloan–Kettering Cancer Center, New York, New York 10021

(Received 15 June 1987; accepted for publication 14 December 1987)

Experimental determination of the dose kernel in high-energy x-ray beams

Crister P. Ceberg and Bengt E. Bjärngard
Department of Radiation Oncology, Roger Williams Medical Center, Brown University, Providence, Rhode Island 02908-4735

Timothy C. Zhu
Department of Radiation Oncology, Shands Cancer Center, University of Florida, Gainesville, Florida 032610-0385

(Received 26 June 1995; accepted for publication 12 December 1995)

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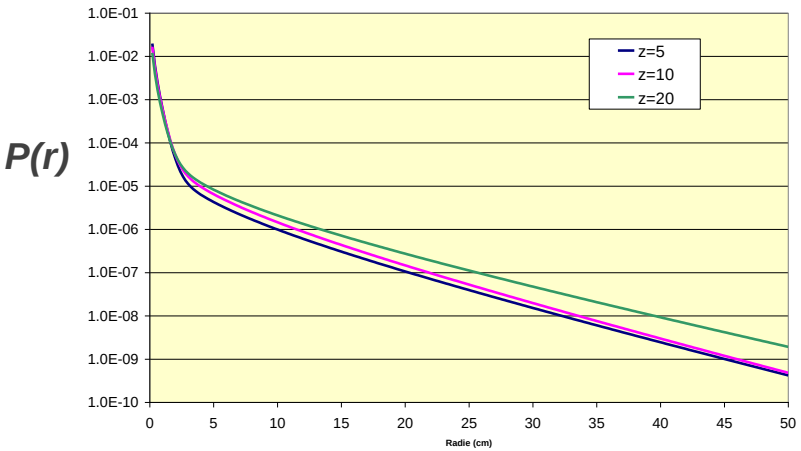
Example – MasterPlan PB

» Pencil-beam kernels based on Monte Carlo calculated point-spread kernels, integrated and fitted to depth dose curves

» Separates primary and scatter components

» Heterogeneities handled by effective path-length (*i.e.* only longitudinal scaling)



$$p(r,z) = \frac{A(z)\cdot e^{-a(z)r}}{r} + \frac{B(z)\cdot e^{-b(z)r}}{r}$$

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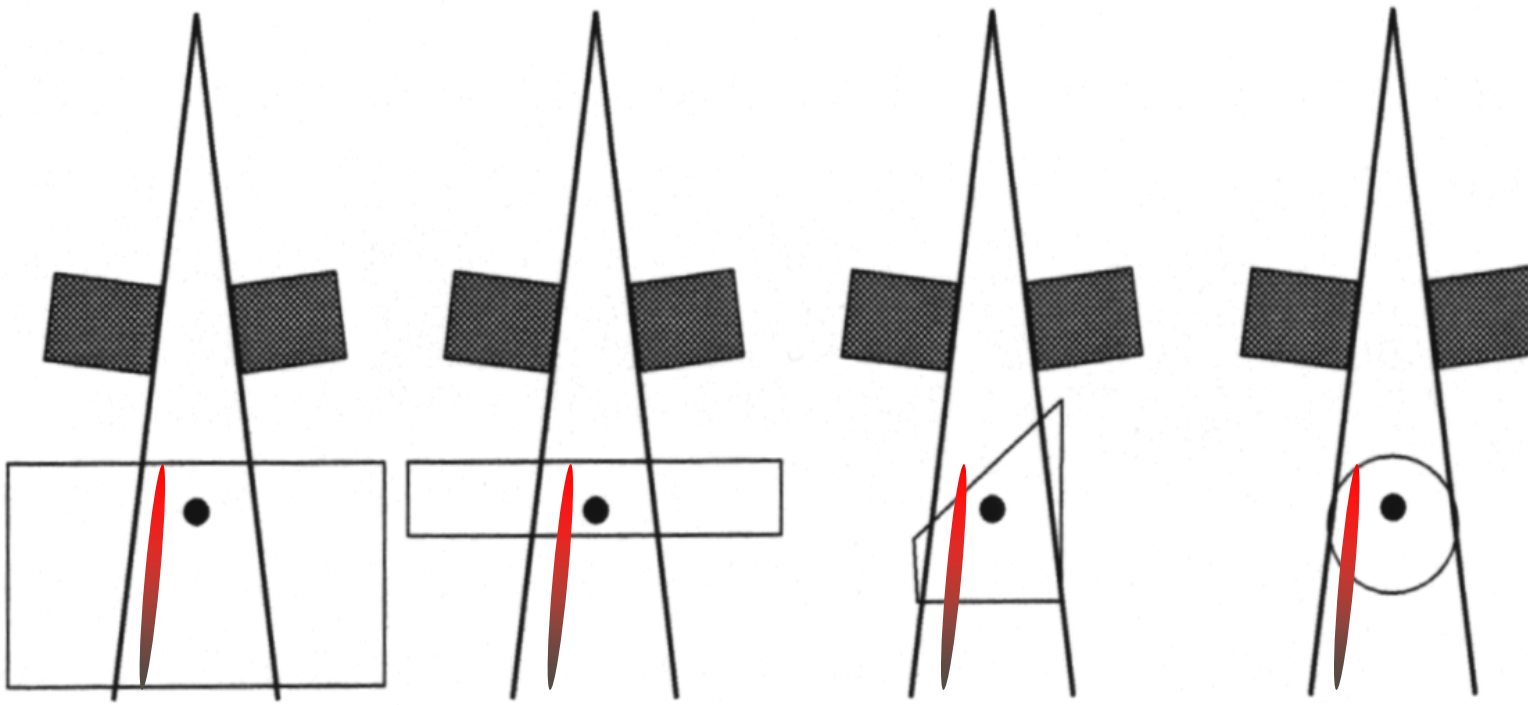
Pencil-beam limitations

» Assumes scatter-dose integration at effective depth



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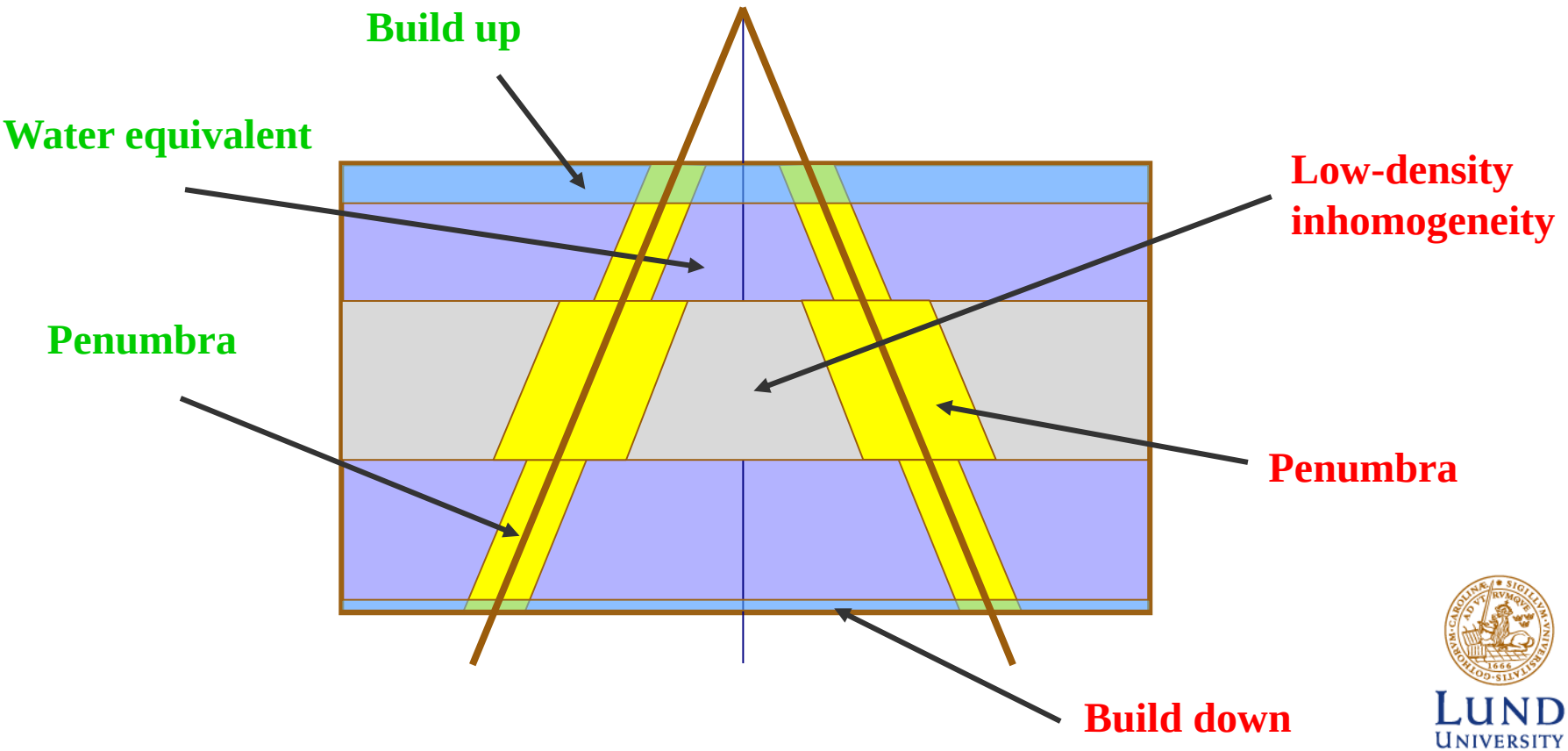
Pencil-beam limitations

» Assumes electron equilibrium in inhomogeneities



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Example – Eclipse AAA

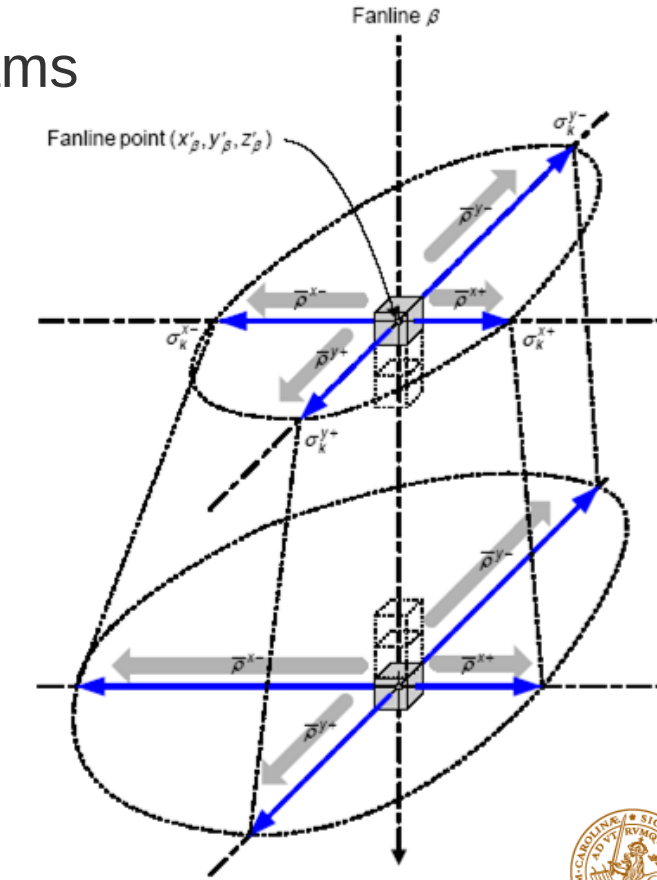
» Monte Carlo calculated pencil-beams

» Divergent, finite-size beamlets

» Heterogeneity correction

– Effective depth in longitudinal direction

– Lateral density-scaling



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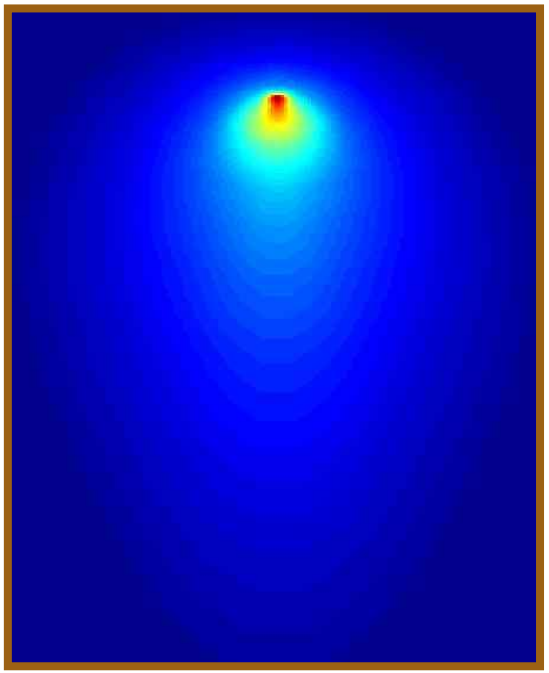
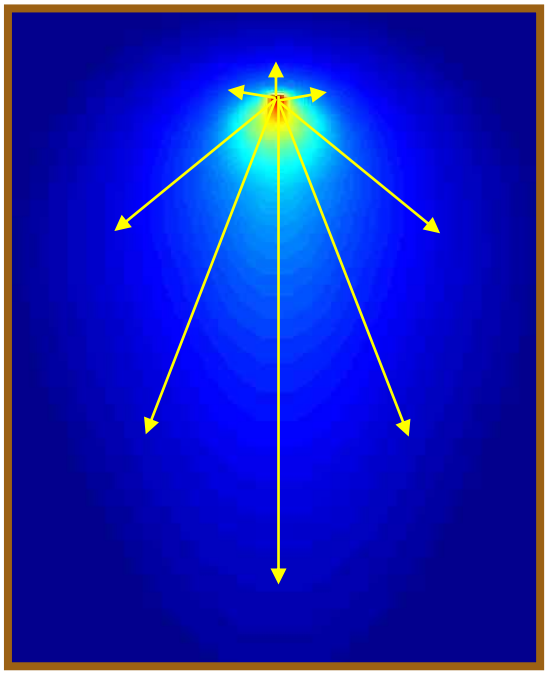
Collapsed-cone approximation

» The kernel is ”collapsed” to a finite number of cones



Continuous Dose

Spread Kernel



Discrete Dose

Spread Directions

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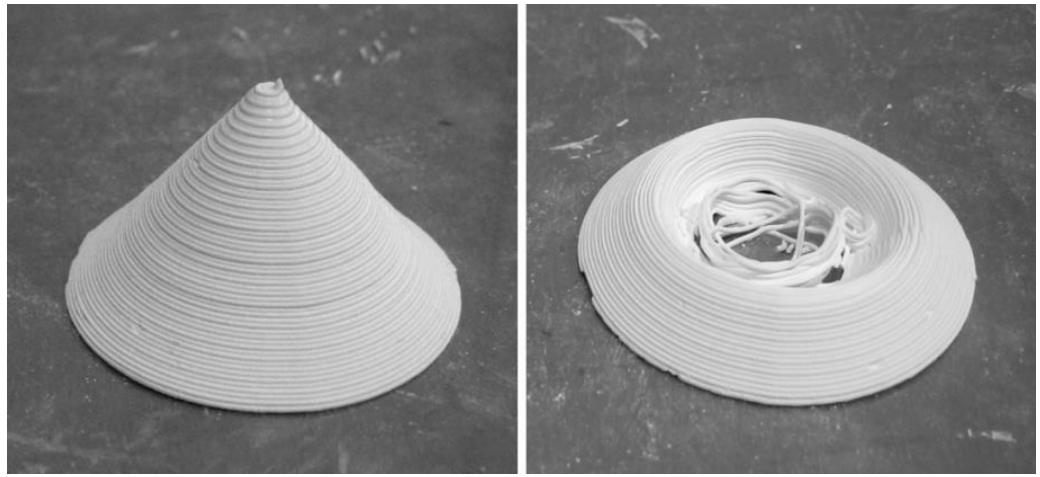
Collapsed-cone approximation



...not so

...more like so

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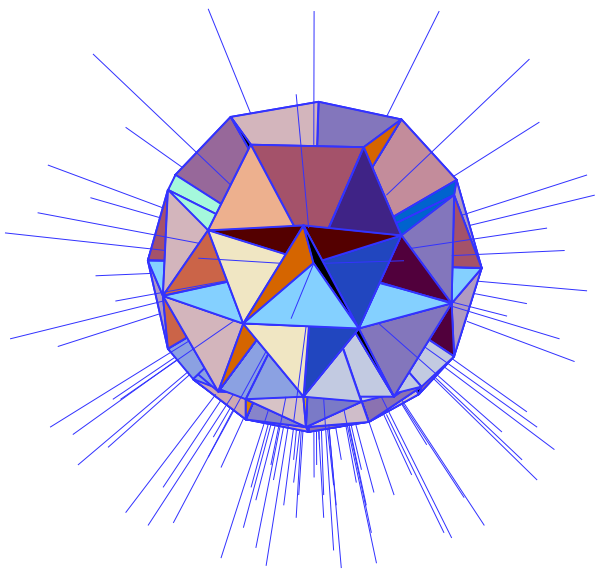
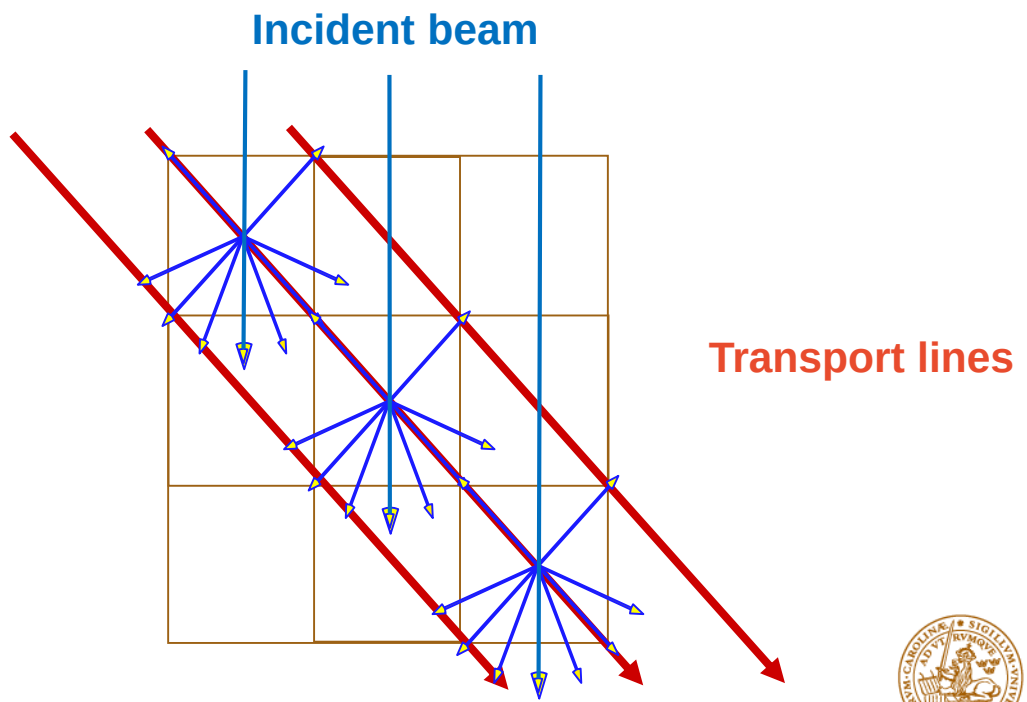
Collapsed-cone approximation

» Fixed number of transport directions (”cones” or ”channels”)

» >100 cones are required





Ahnesjö, Med Phys 16:577, 1989

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Flexible approach

» Density scaling along each transport ray

» Heterogeneity correction in all directions (3D)

» Can account for beam-hardening and off-axis softening

» Can include kernel tilt in divergent beams

» Sparse or variable calculation grid (”multi-grid” or ”adaptive”)

- Gradient dependent
- Interpolation

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Summary

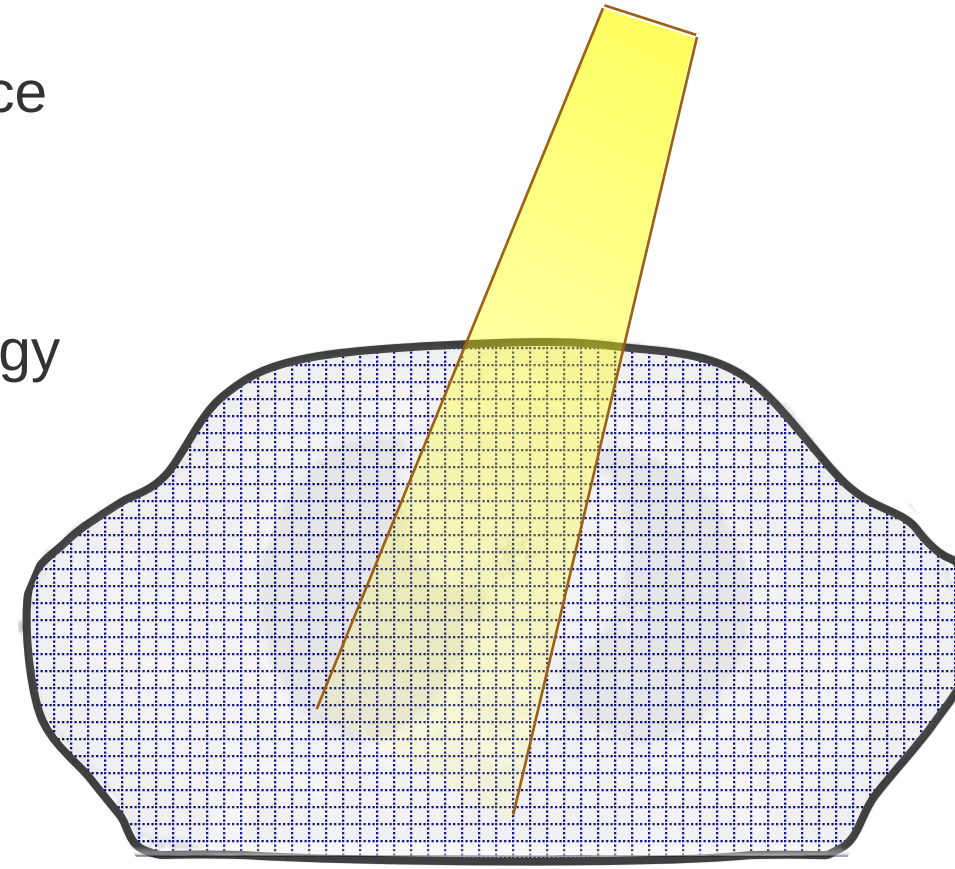
» Incident photon fluence

» Raytracing

» Redistribution of energy

  – Pencil-beam

  – Collapsed cone



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Summary

» Incident photon fluence

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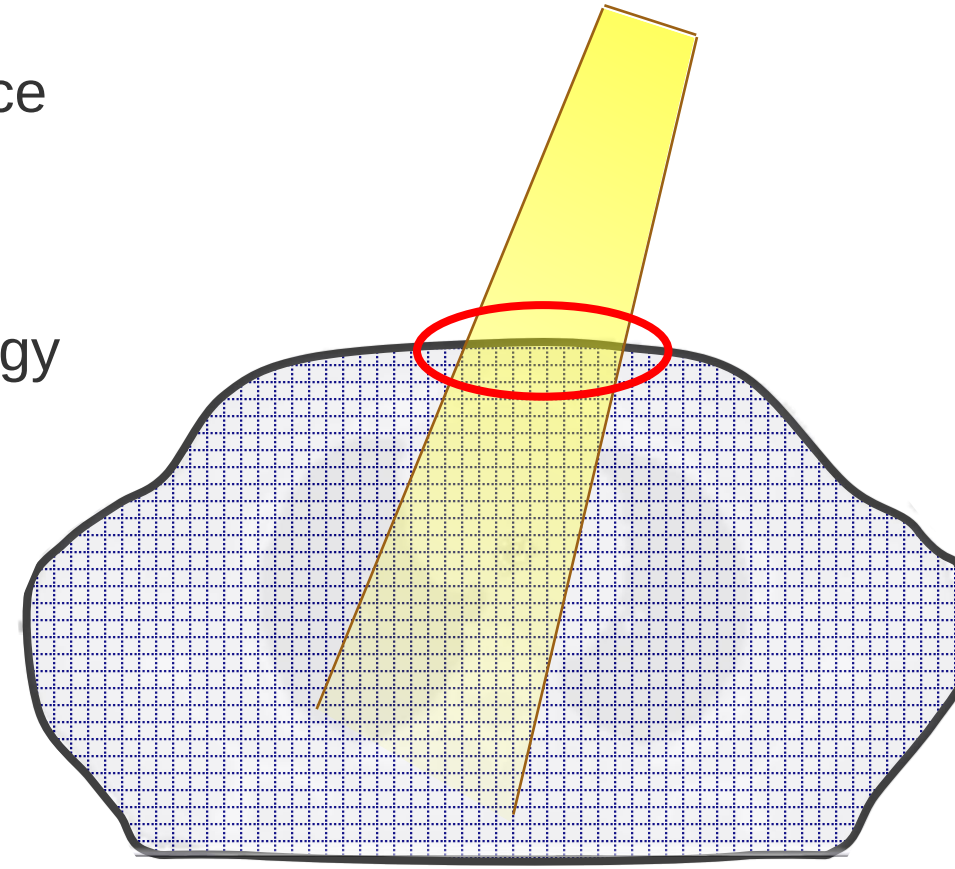

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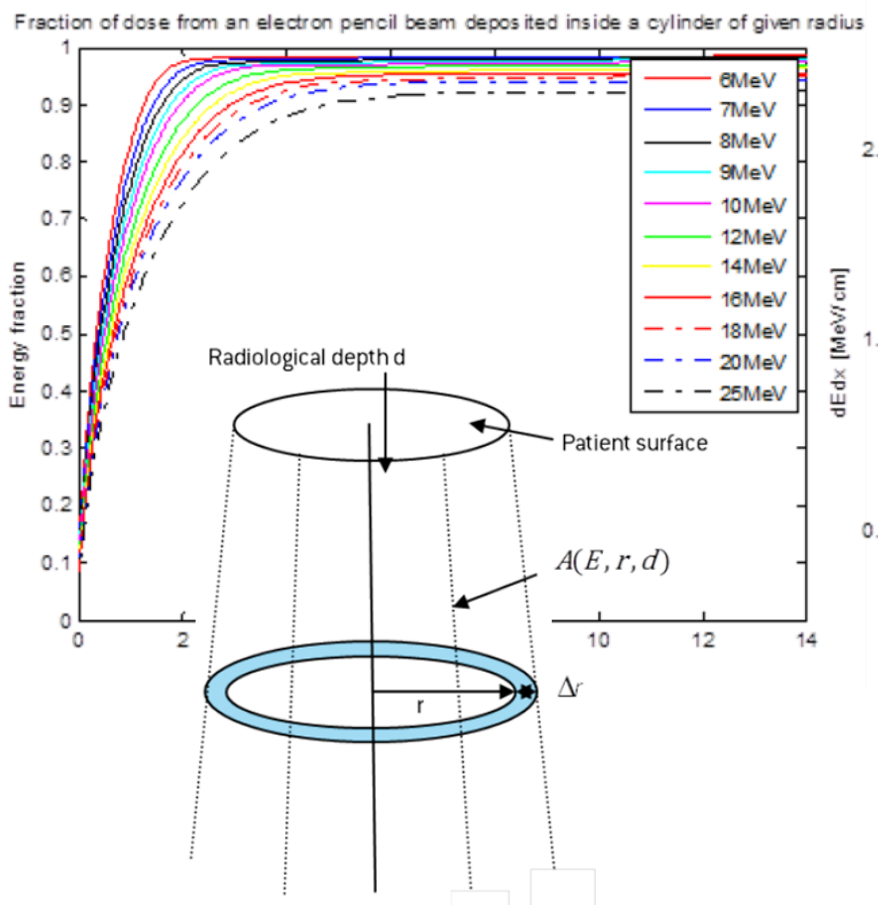
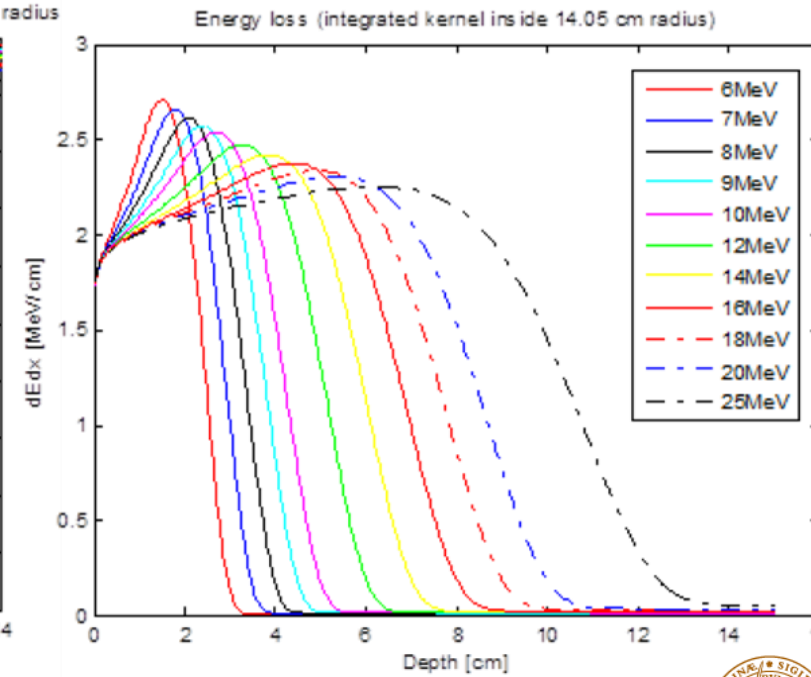
Electron contamination

» Integration of electron pencil-beam kernel





RayStation

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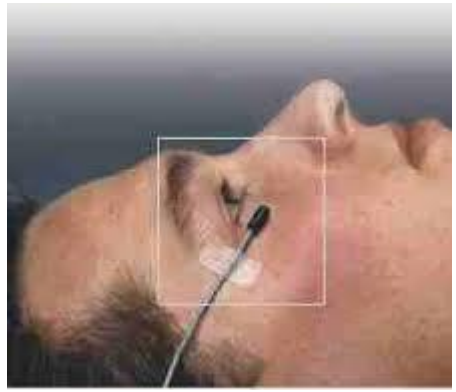
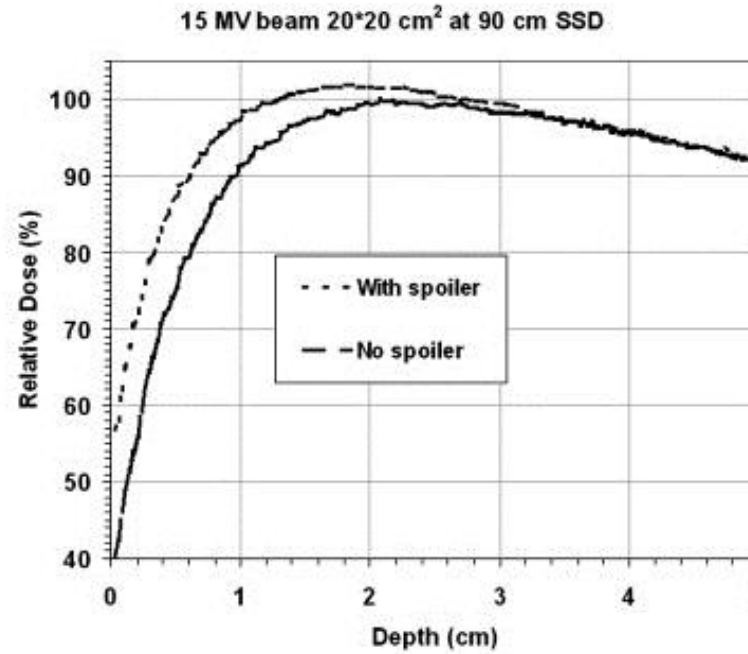
Electron contamination

» Important for *in vivo* dosimetry





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Comparison between different algorithms

» Type A models

– Primarily based on effective-path length correction

– Longitudinal scaling only

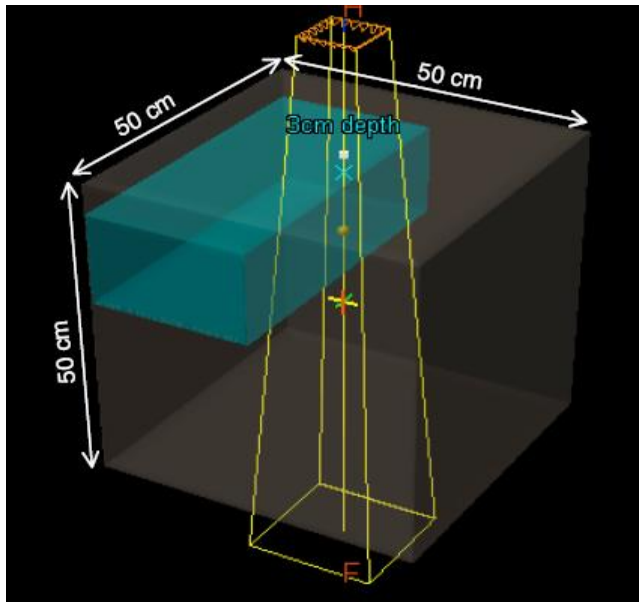
» Type B models

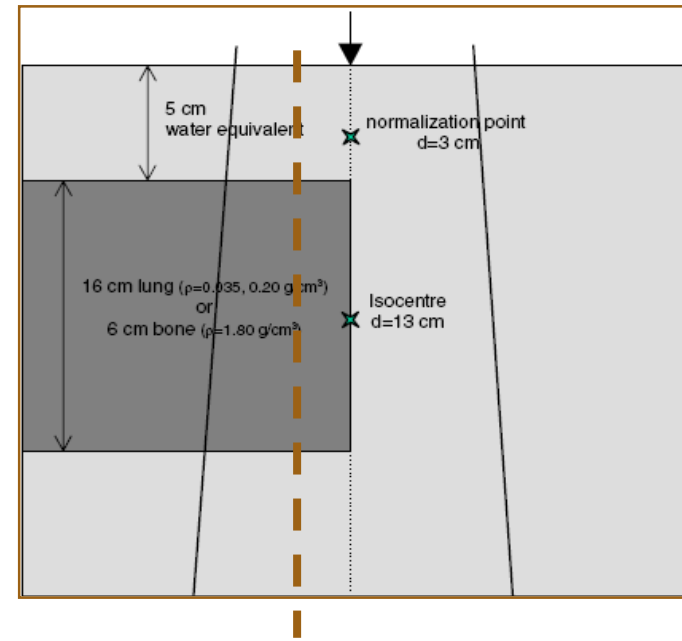
– Approximate handling of lateral electron transport

– Longitudinal and lateral scaling

Comparison between different algorithms

» Water phantom with low-density (0.2 g/cm^3) ”lung” insert





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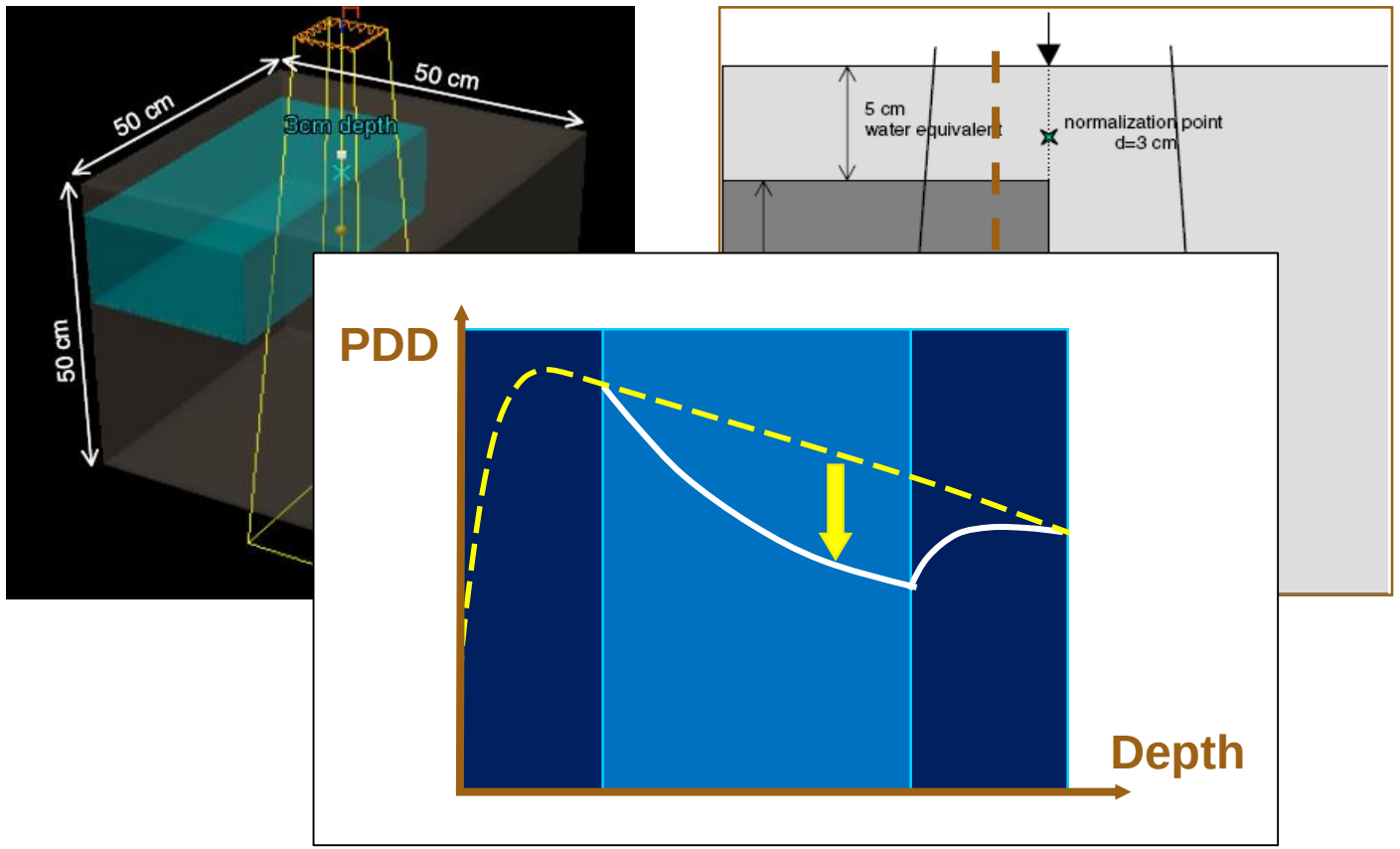
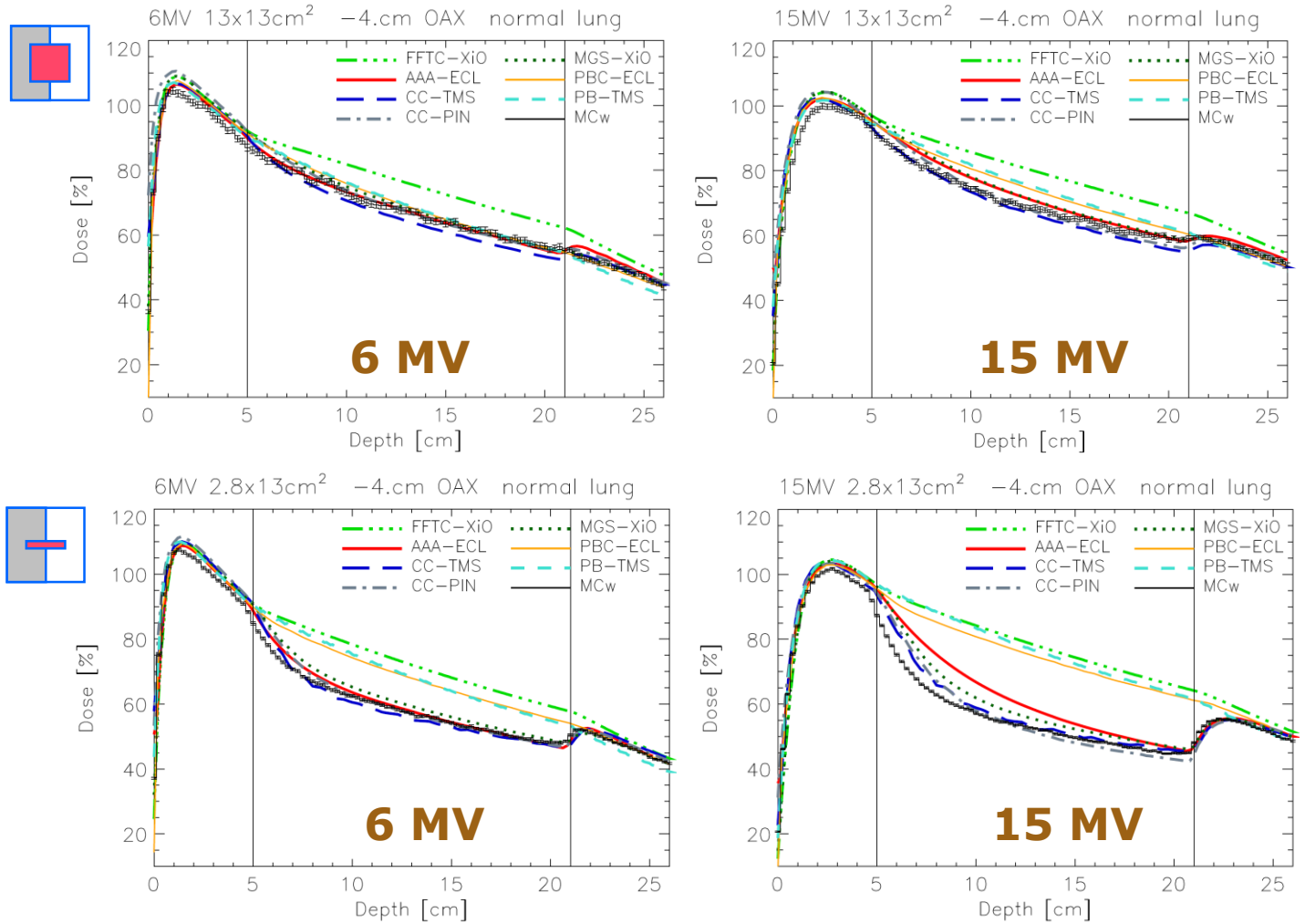
Comparison between different algorithms

» Water phantom with low-density (0.2 g/cm^3) ”lung” insert



Comparison between different algorithms



Fogliata et al, Phys Med Biol, 2007

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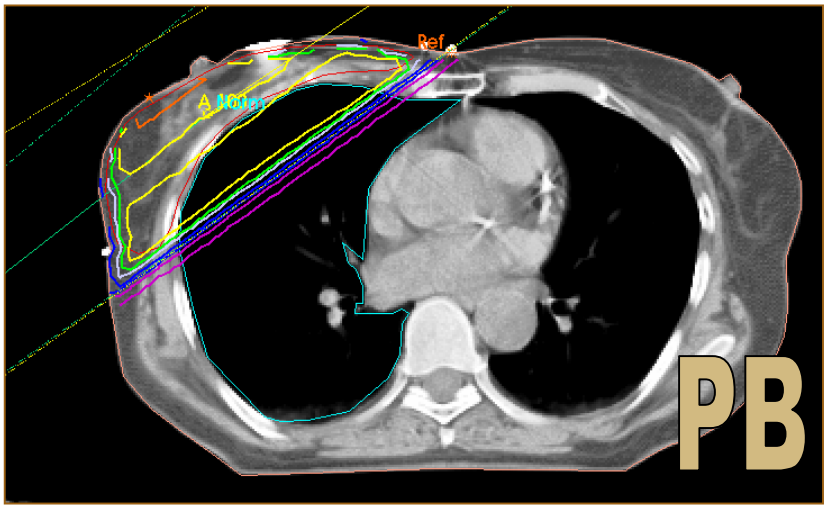
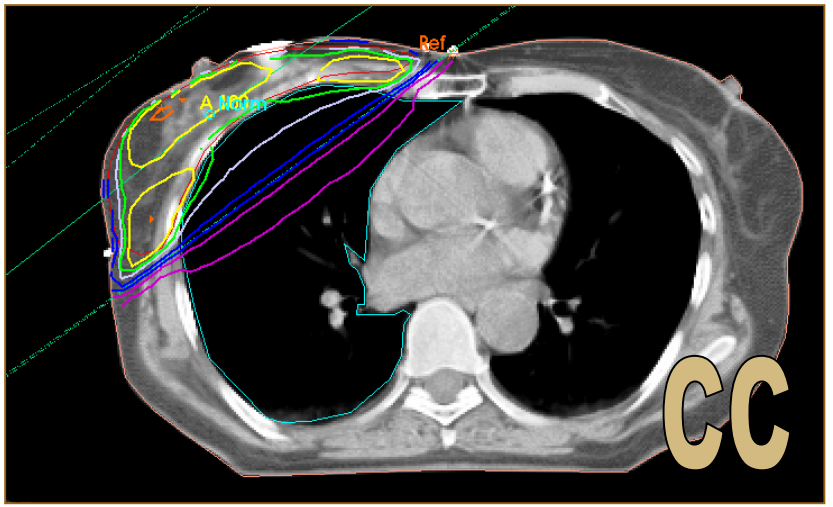
Clinical example – breast treatment

10, 30, 50, 70, 90, 95, 100 & 105 %





MasterPlan

CC: Slightly lower dose to breast and especially in lung in proximity to the target. However, larger irradiated lung volume

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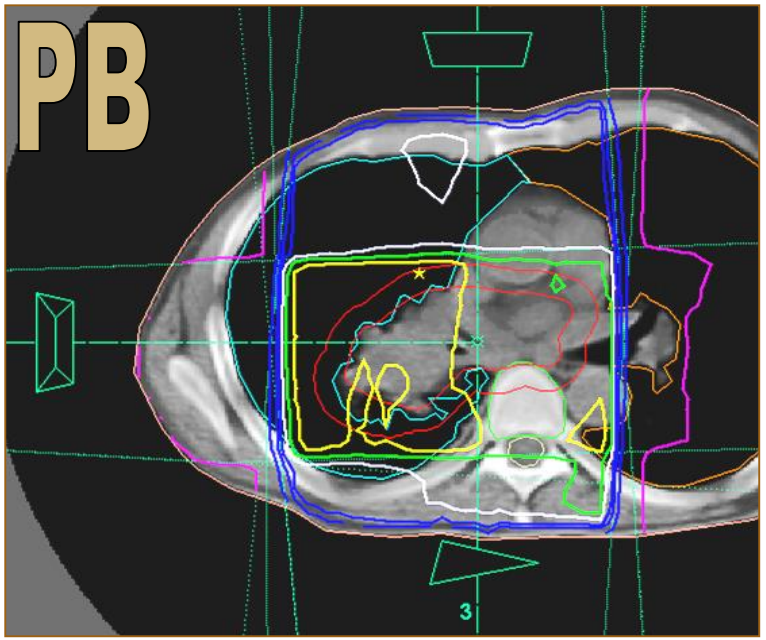
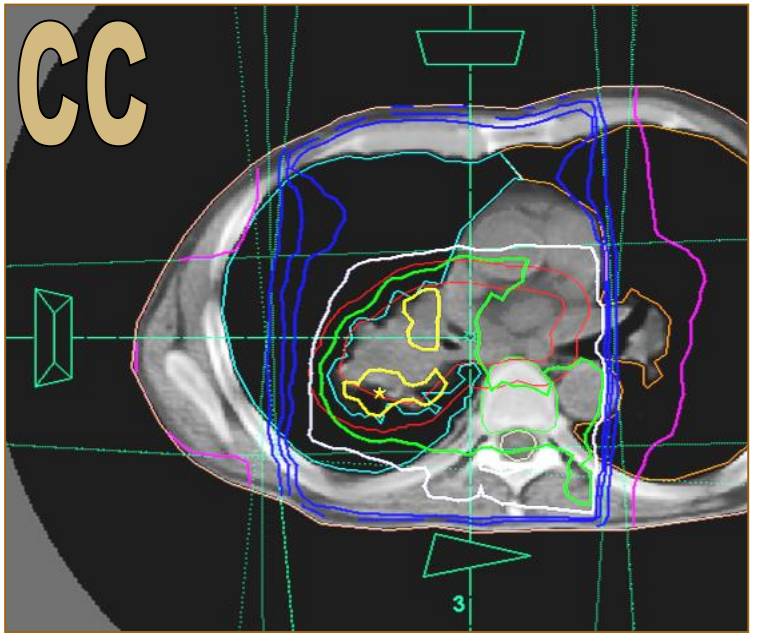
Tommy Knöös

Clinical example – lung treatment

10, 30, 50, 70, 90, 95, 100 & 105 %





MasterPlan

CC: Average dose in PTV 2-4% lower, and wider penumbra. Max dose to ipsi-lateral lung 10% lower.
Similar dose to contra-lateral lung.

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Tommy Knöös

Two atoms are sitting in a field of ionizing radiation.

One atom says, "I think I lost an electron."

The other says, "Are you sure?"

The first atom says, "I'm positive!"

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