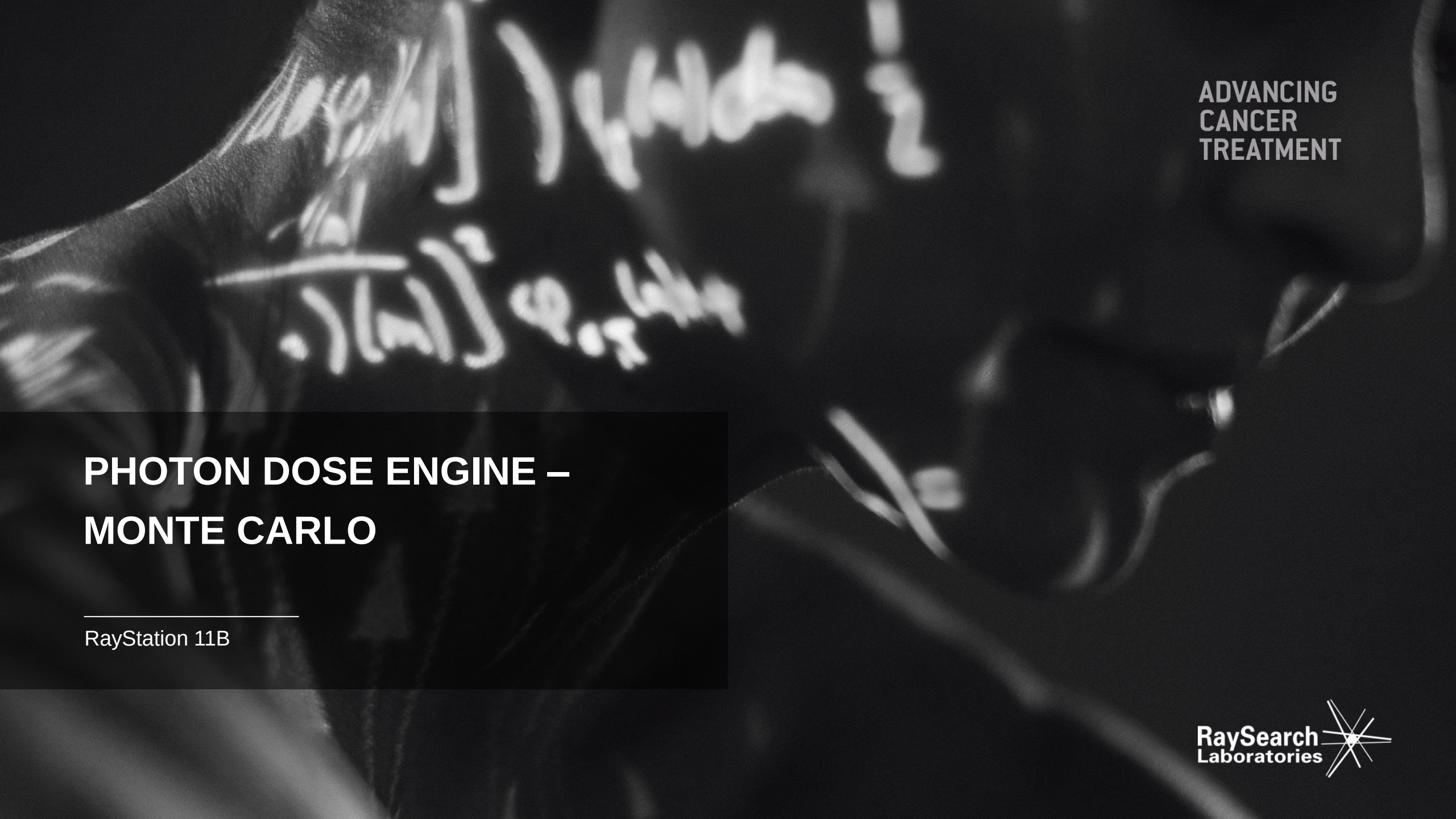

ADVANCING
CANCER
TREATMENT

PHOTON DOSE ENGINE – MONTE CARLO

RayStation 11B

RaySearch Laboratories

OVERVIEW

- General
- Why MC?
- Photon MC in RayStation
- Physics
- Differences to CC

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GENERAL

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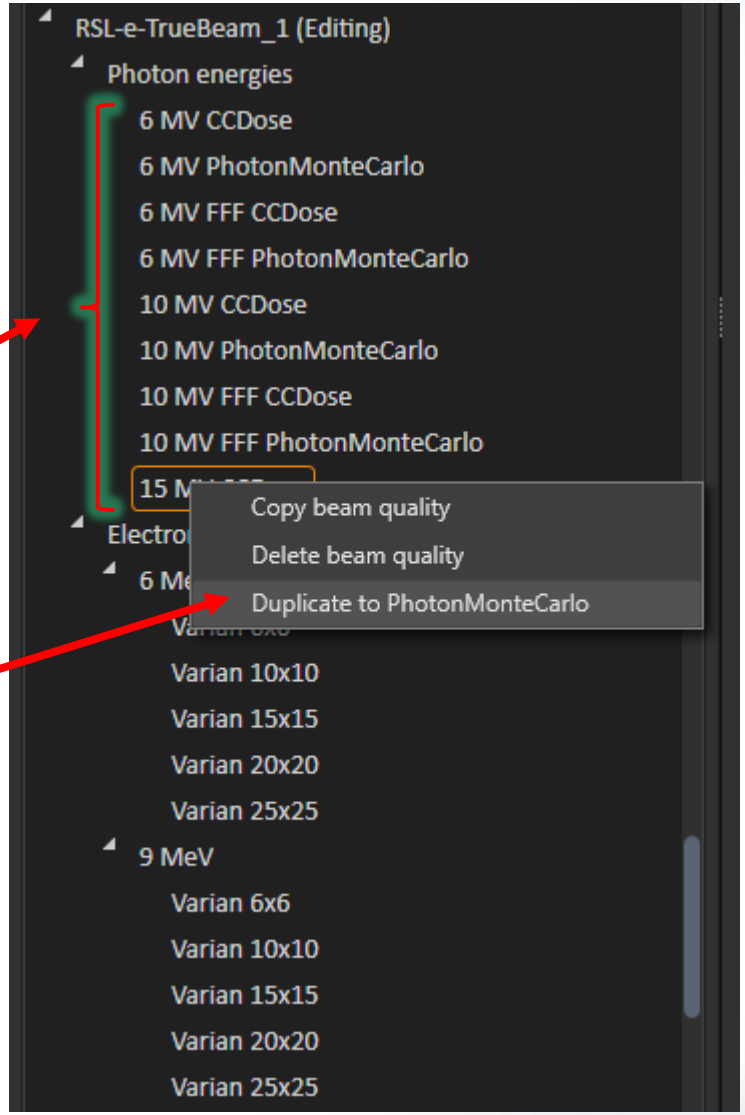
RELEASED IN RAYSTATION 9B

- Tested by a small number of clinics, joint discussion before clinical use
- Possible to have both CC and MC with different fluence modes (FF, FFF and SRS) for the same energy.
- Possible to duplicate the CC model to use as a starting point.
- *RayPhotonMonteCarlo* License required to approve/export. License is free of charge.



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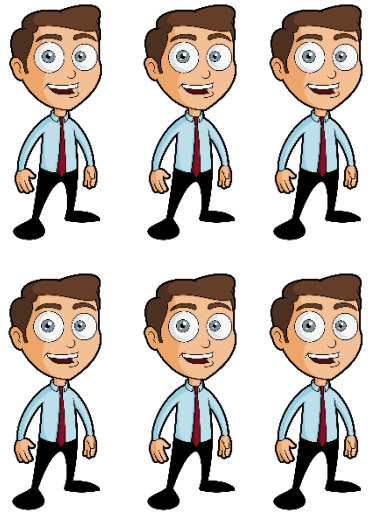
HARDWARE

- CUDA – GPU only
  - Needs at least 4GB of GPU memory to compute very simple plans.
  - For real clinical use more GPU is needed
  - Compute capability 3.2 (Quadro K6000 or newer)
  - No recomputation without ECC

CPU

VS

GPU



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WHY MC?

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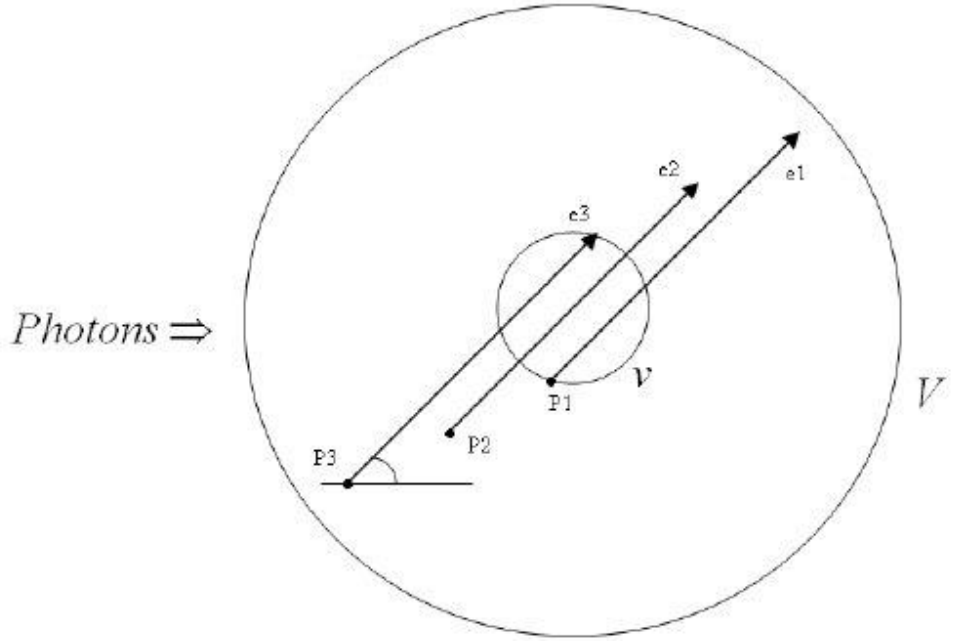
ELECTRONIC EQUILIBRIUM

- The same number of electrons with the same energy distribution leaves and exits a volume
- Lack of equilibrium when gradients in material and fluence < range of electrons
  - Small fields
  - Higher energies
  - Large density/material gradients
  - Low densities



AK Al-Basheer et al. (2007), Electron Dose Kernels to Account for Secondary Particle Transport in Deterministic Simulations; *Nuclear Technology* 168 (3)

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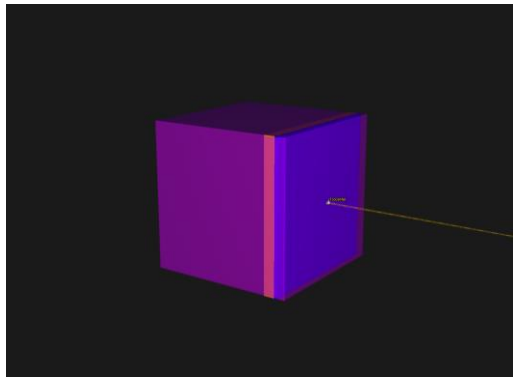
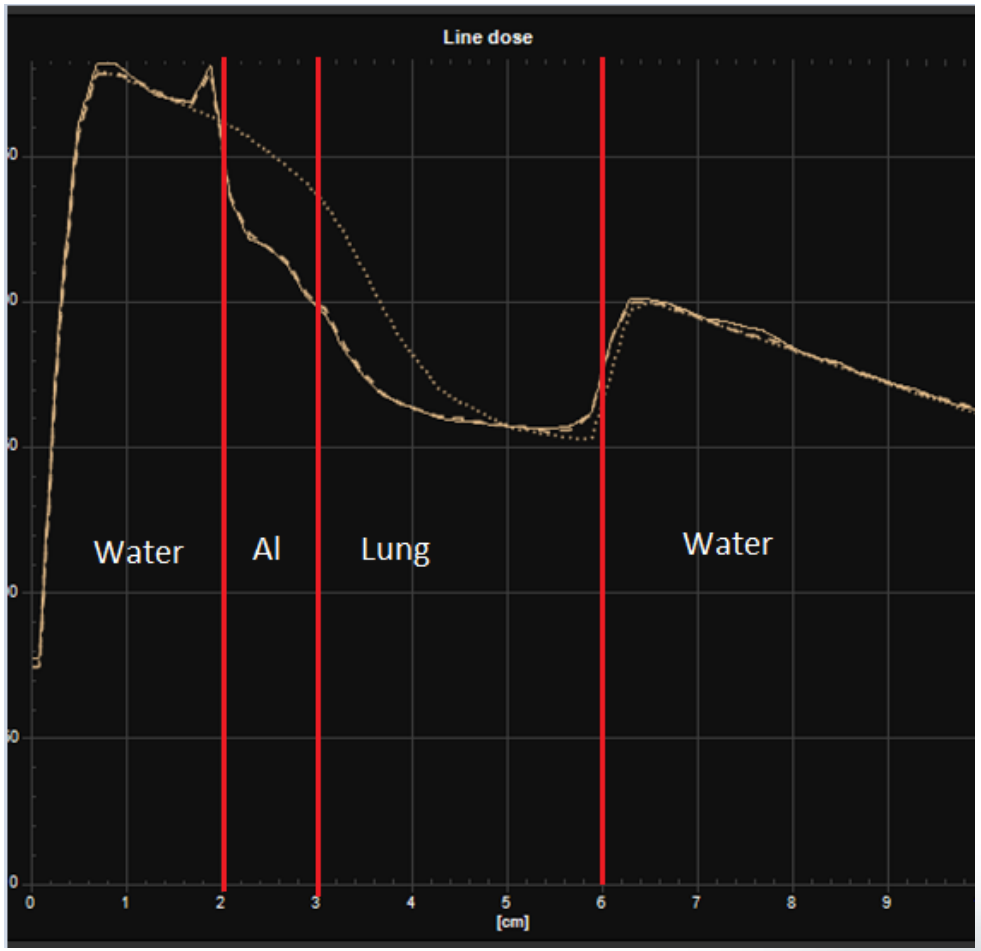
MATERIAL GRADIENTS

- ICCR phantom (Al and lung slabs in water)
- 2 MeV photons, 1.5x1.5 cm^2 field
- Dw/Dm ~0.8 in Al, ~1 in lung





D. W. O. Rogers and R. Mohan, “Questions for comparisons of clinical Monte Carlo codes,” in *Proceedings of the 13th ICCR*

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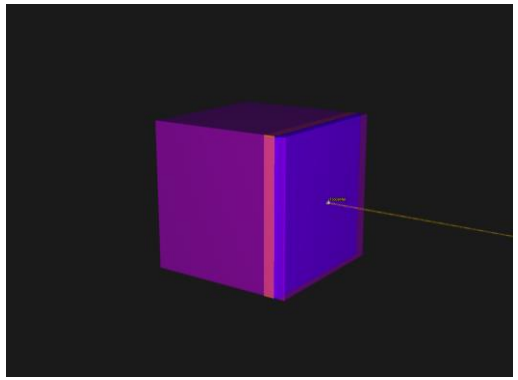

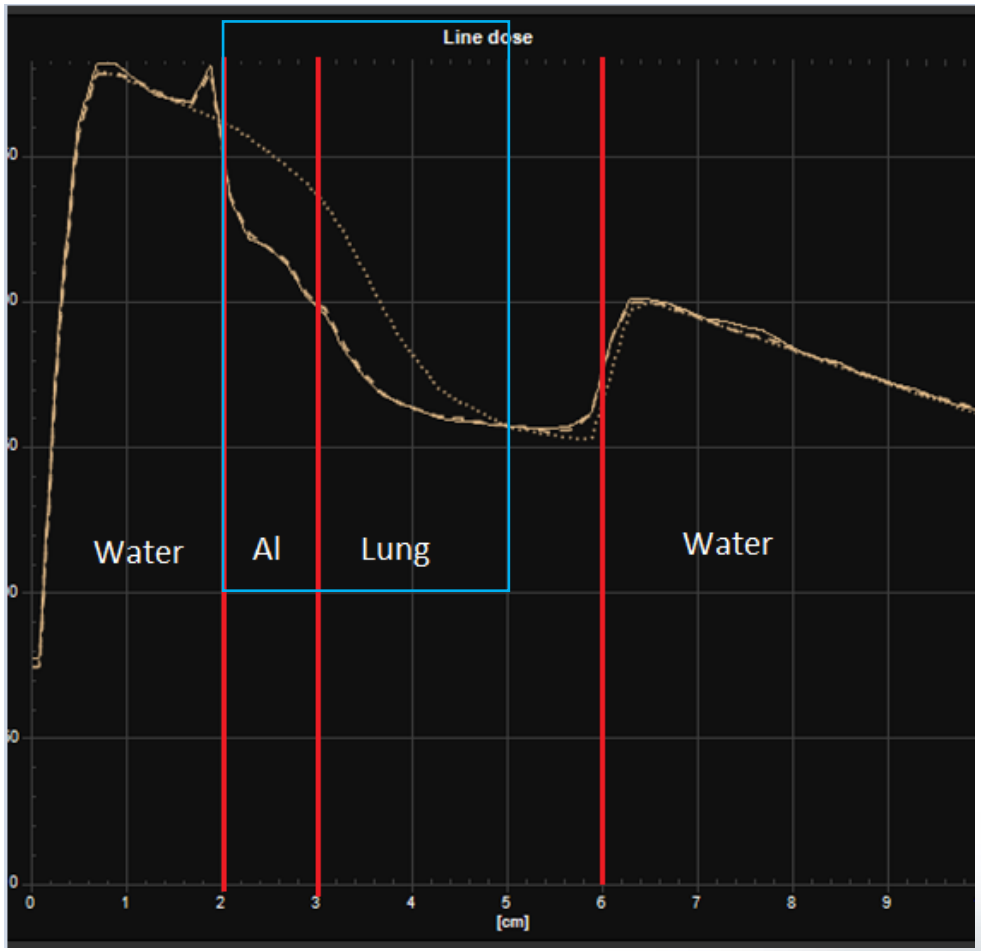

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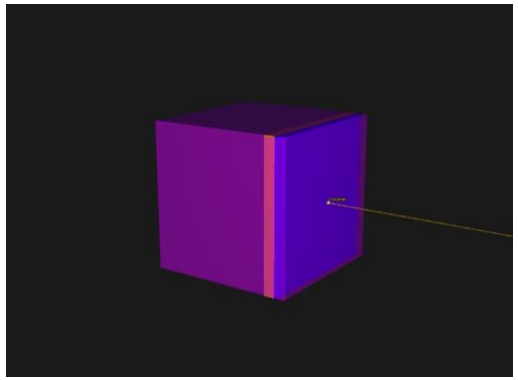

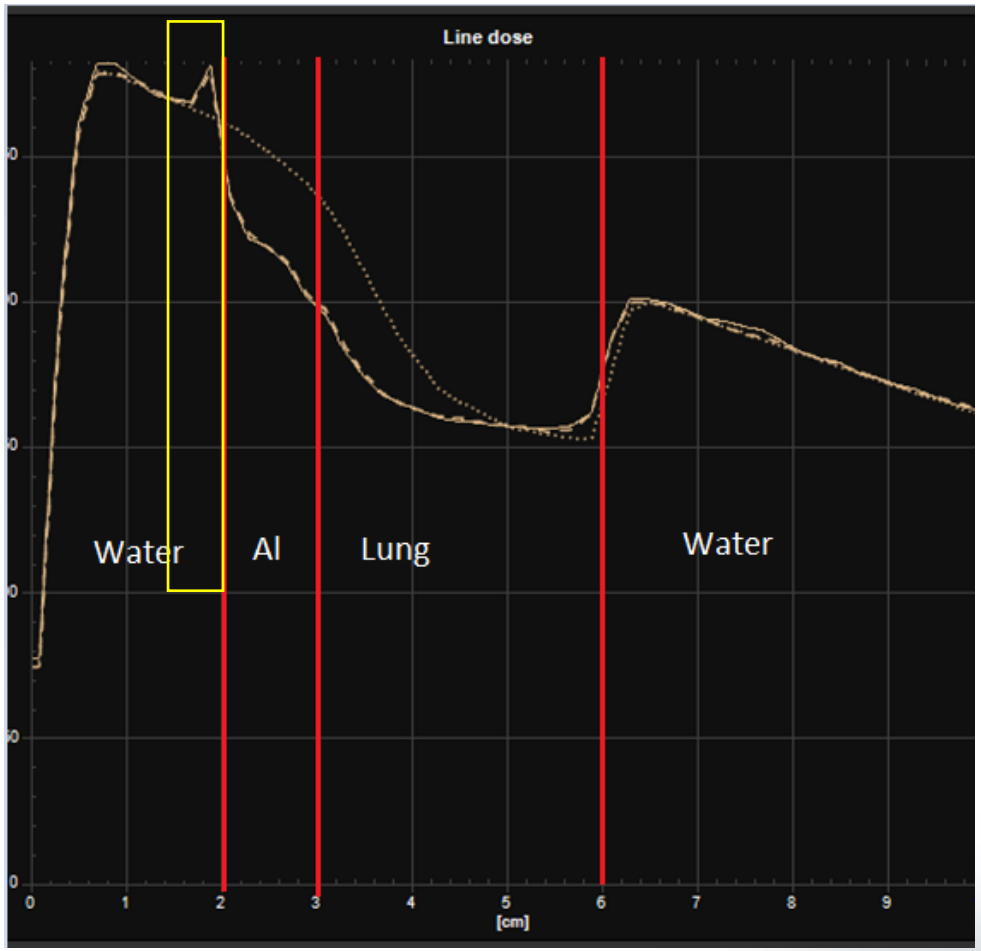

D. W. O. Rogers and R. Mohan, “Questions for comparisons of clinical Monte Carlo codes,” in *Proceedings of the 13th ICCR*

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PHOTON MC IN RAYSTATION

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FLUENCE ENGINE

- Same “Fluence engine” as for CC
  - Same “Beam measurements data” for commissioning
  - Same Beam model parameters in RayPhysics

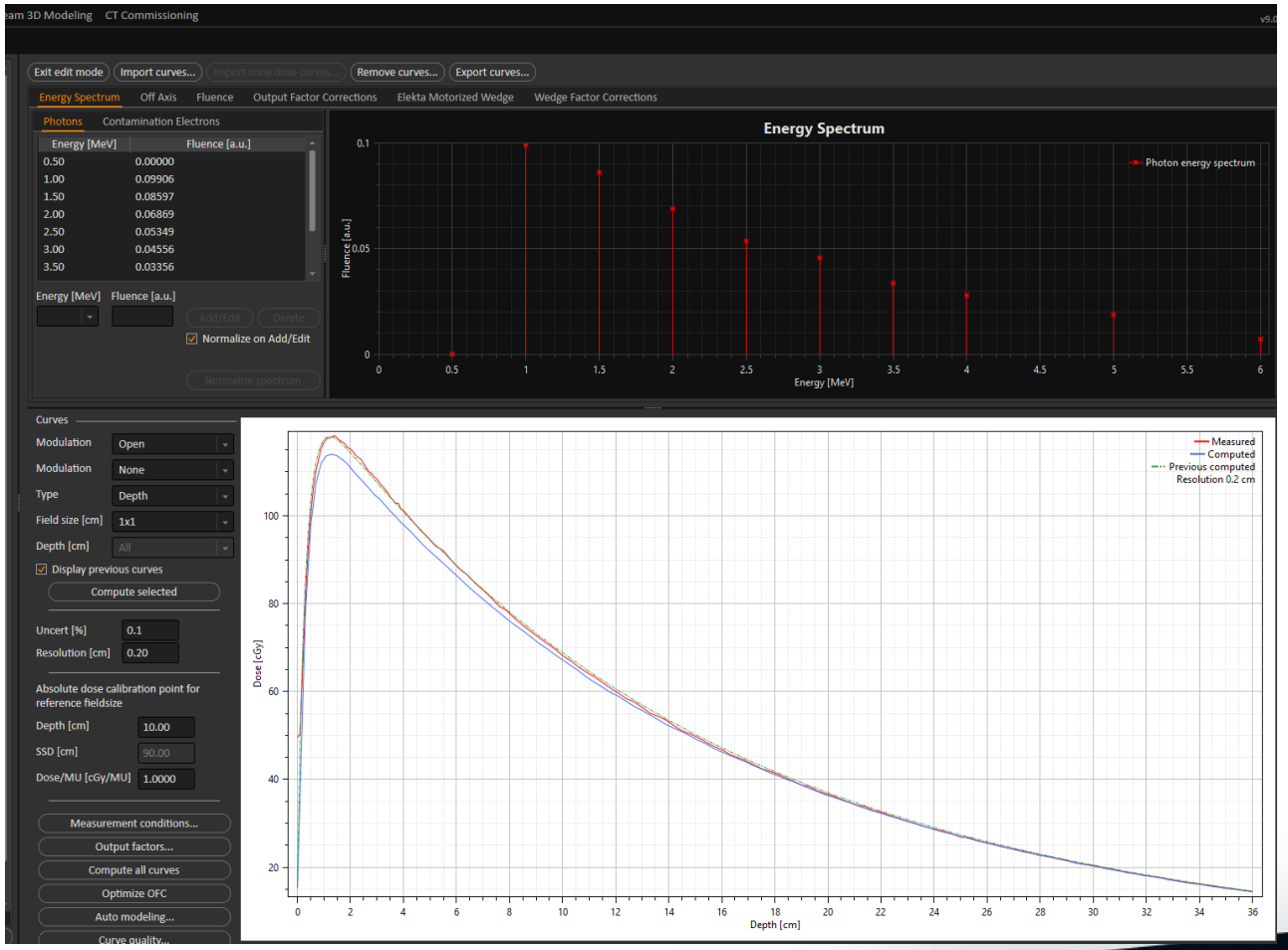
    BUT

  - **NOT** possible to use the **same** beam model parameter **values** for both dose algorithms
  - The MC dose calculation is more sensitive to variations in the “**Energy Spectrum**” shape compared to the CC

    → More important to have a physically meaningful spectrum than with the CC

CC dose engine

MC dose engine

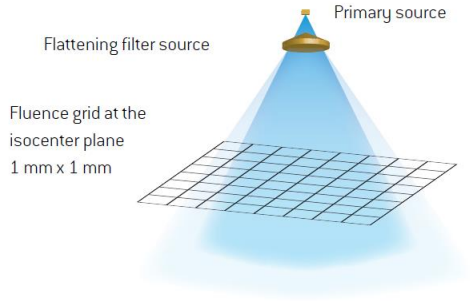


RaySearch Laboratories

FLUENCE

- Fluence distribution calculated like for CC and same 1mm grid
- Fluence distribution converted into tables that can be sampled from by the MC algorithm
- Fluence assumed constant over each pixel
- A pixel is sampled from the fluence distribution
- **Position** of the particle sampled uniformly within the pixel

Energy Fluence



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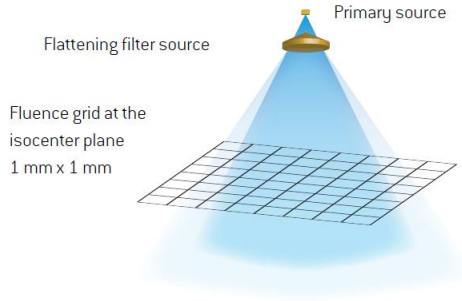
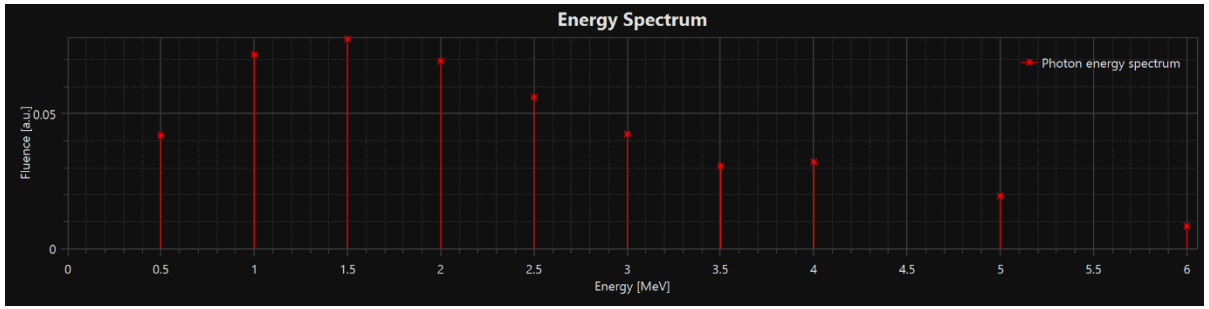
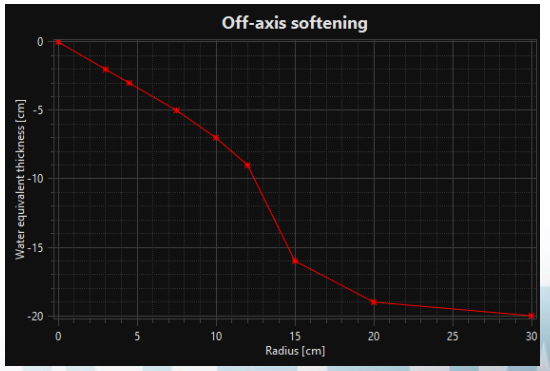
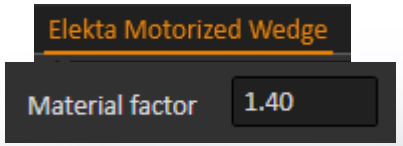
Energy Fluence









RaySearch Laboratories

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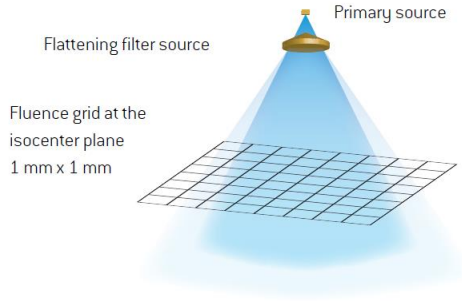
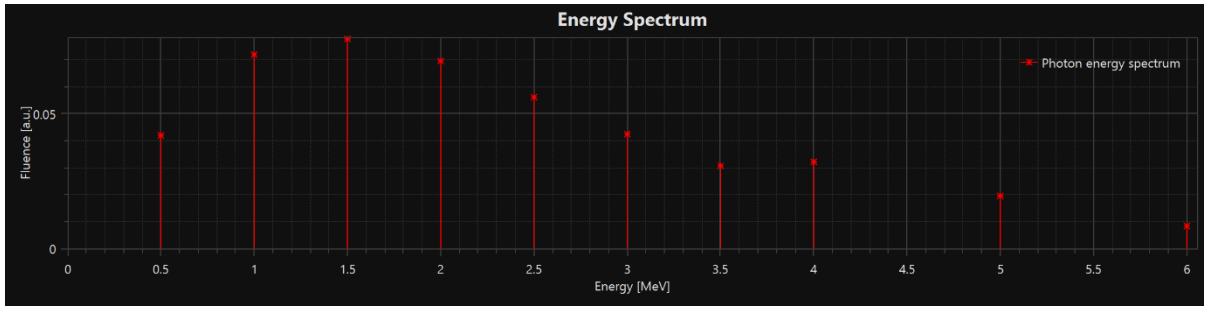
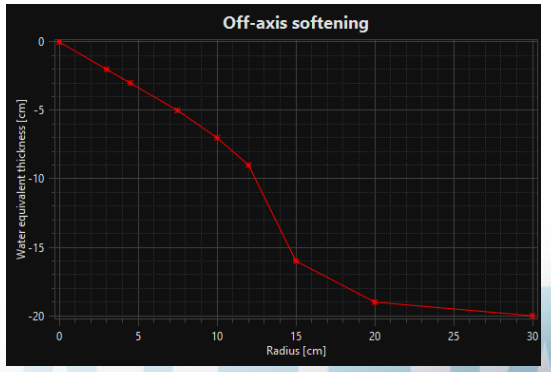
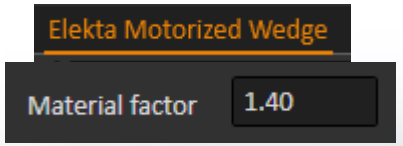
- A pixel is sampled from the fluence distribution
- **Position** of the particle sampled uniformly within the pixel
- **Energy** sampled from the local spectrum in the pixel taking **Off-Axis Softening** and **Wedge** thickness into account (**Material Factor**)
- All photons and electrons **initial direction** from the primary source towards the fluence position (like TERMA computation)

Energy Fluence









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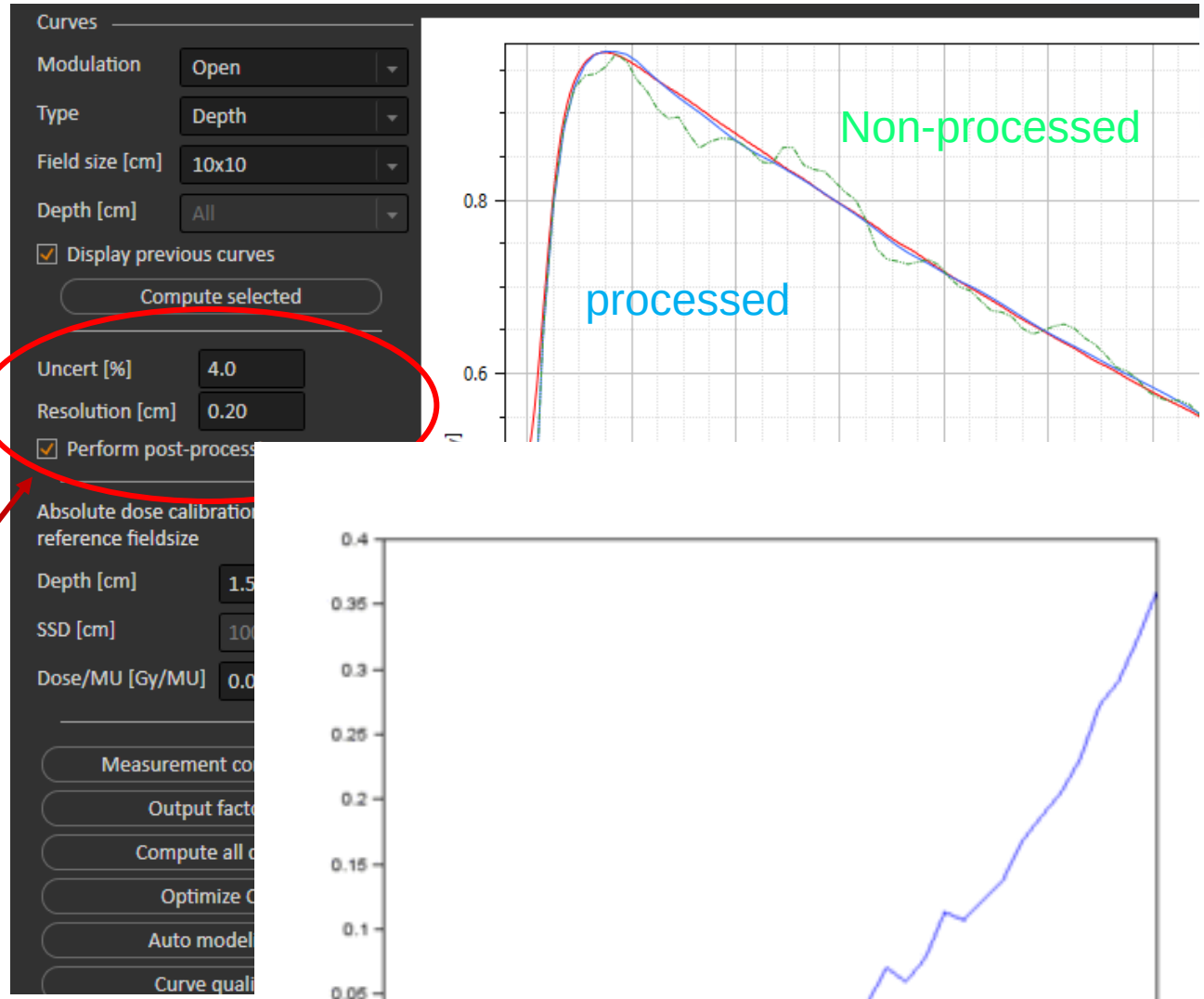
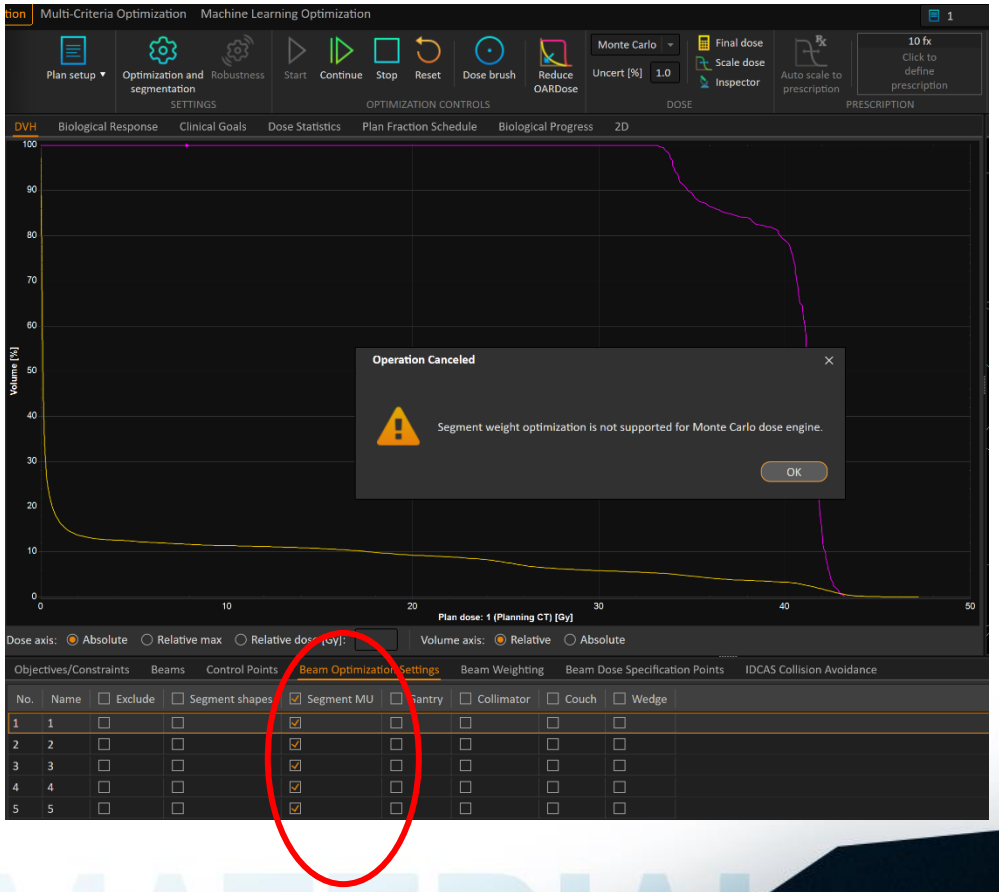
IN RAYPHYSICS

- Uncertainty must be **≤ 0.5%** to be able to commission it
- The same beam model parameters as for the CC dose engines but different values to be optimized
- Post processing smoothens curves. Easier to assess curves (especially for larger field sizes) with high uncertainty to speed up modeling.
- Not possible to commission machine with post processed curves, only a tool for intermediate modeling.



IN RAYSTATION

- Developed by RaySearch and makes no use of any external software packages
  - Accuracy for RT dose calculation but optimized for speed
- All treatment techniques (except Tomo)
- Computes dose and statistics per fraction group and not per beam
- Works wherever it is possible to compute CC-dose except:
  - Segment weight optimization
  - Fallback planning
  - Auto-breast
- Dose to medium



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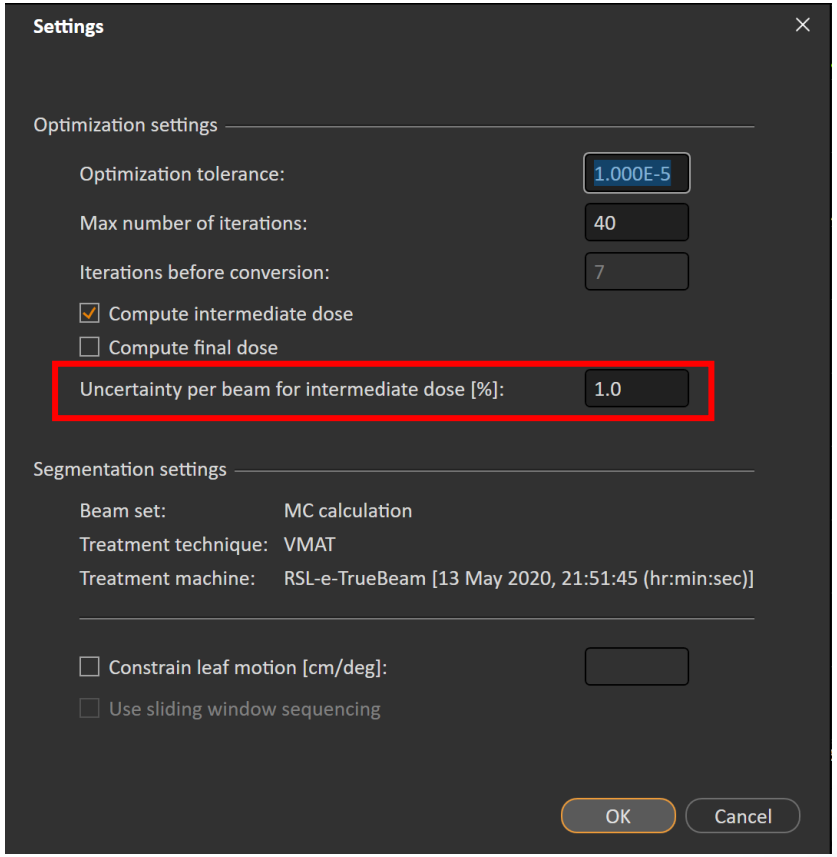
OPTIMIZATION MODULE

- Intermediate dose is computed per beam
  - Define uncertainty per beam
- Works with MCO
- Segment weight optimization not supported
- Note: Be careful with objectives/prescriptions to points or min/max dose
  - Very sensitive to dose uncertainty



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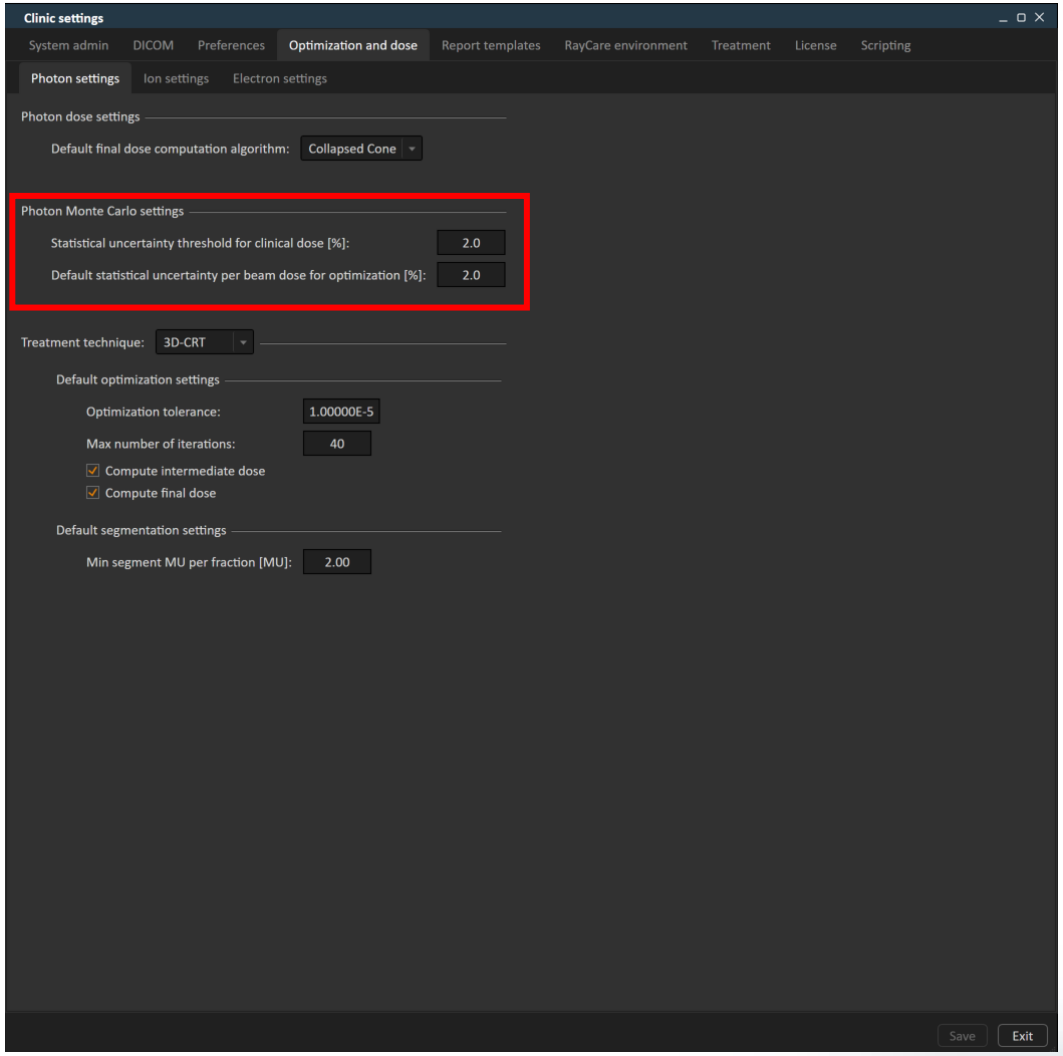
CLINIC SETTINGS

- Set clinical dose threshold. Must be set by the clinic as for protons
- Set default uncertainty per beam for intermediate dose



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PHYSICS

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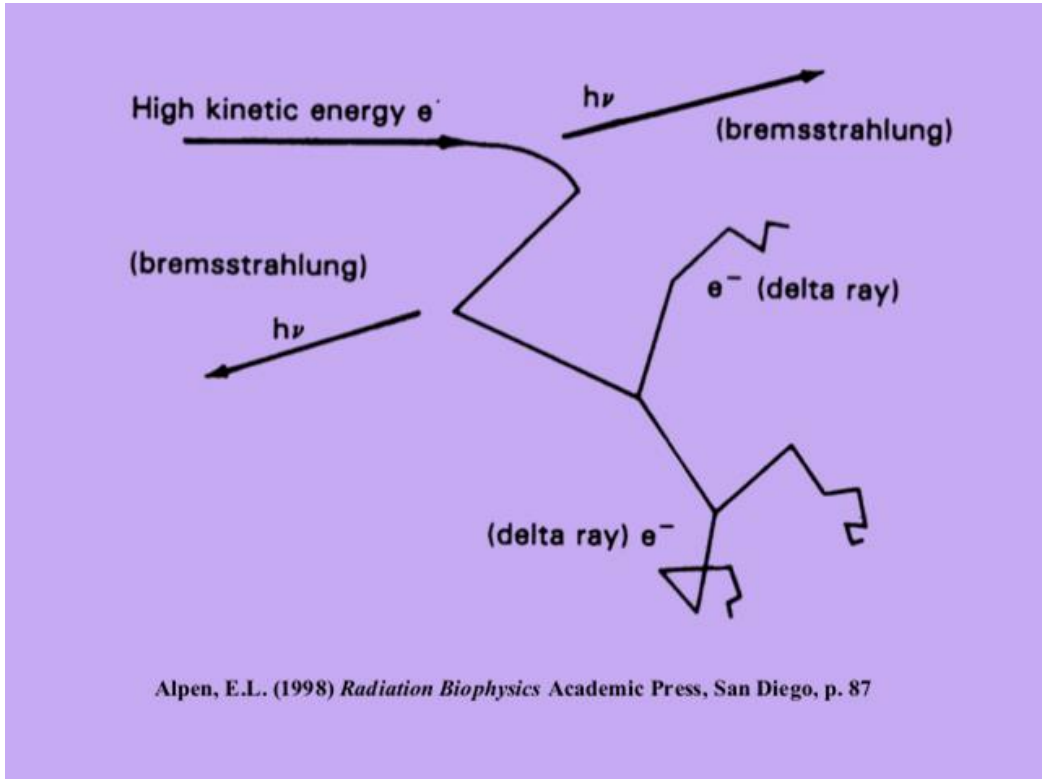
OVERVIEW

- Class II algorithm (condensed history)
- Transports photons, electrons and positrons
- Photons:
  - Compton scattering, photoelectric absorption and pair creation events
- Electrons and positrons:
  - Discrete events: Møller scattering, bremsstrahlung and positron annihilation
  - Multiple scattering using random hinge condensed history method



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DOSE TO MEDIUM

- **Dose to medium D_m^m :**

- Dose to medium with radiation transport in medium D_m^m
- The CC calculated dose to water with transport in water or dose-to-different-density-water D_w^w. Particularly important for: **air**, **bone**, **implants**
- Be aware of the differences and make sure that the **clinical goals are adapted**

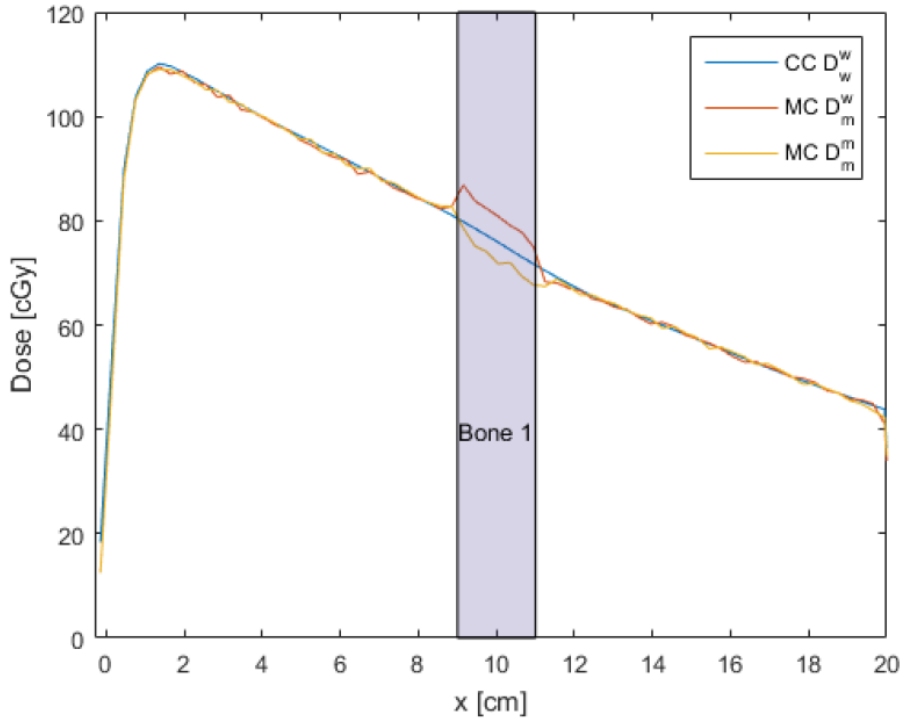

Figure 19. Depth dose in a 20 cm x 20 cm field for a typical 6 MV LINAC with the RayStation 9A D_w^w, non-clinical Monte Carlo D_m^m and non-clinical Monte Carlo D_m^w. The patient geometry is a phantom with a 2 cm Bone 1 slab at 10 cm depth.

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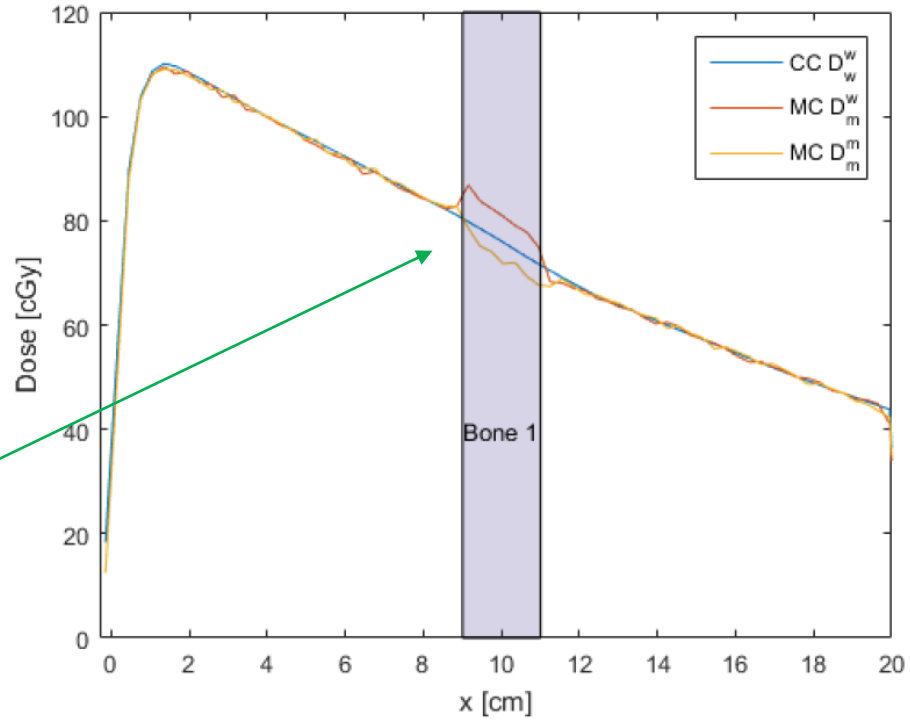
The CC dose to water D_w^w is closer to the MC dose to medium D_m^m than to the converted MC dose to water D_m^w

Similar results of "*Ma et al. Dose specification for radiation therapy: dose to water or dose to medium?; Phys Med Biol 56 (2011)*"



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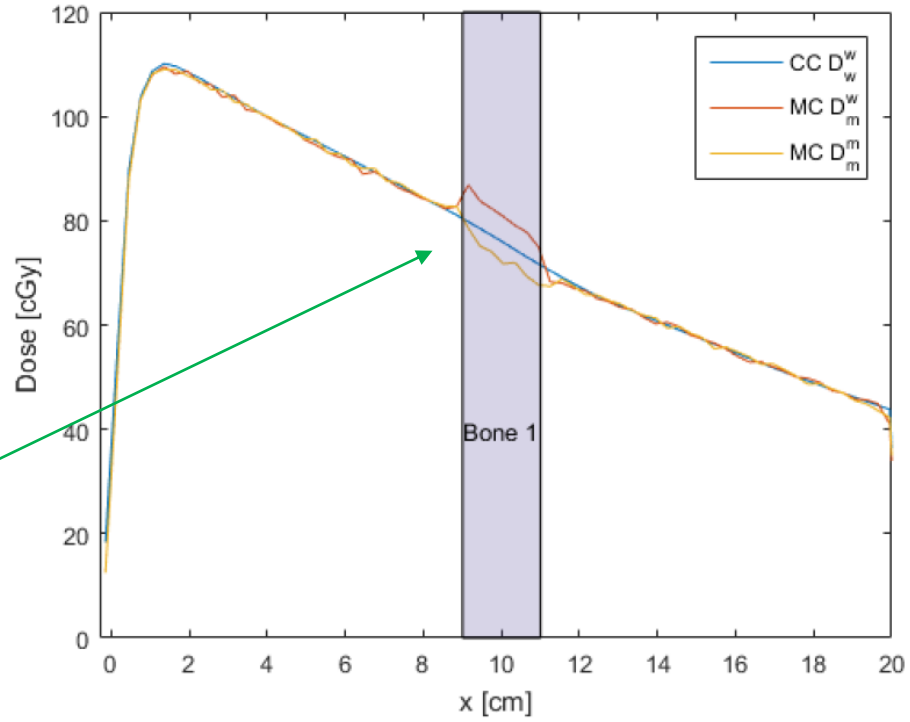
- Newer AAPM Guideline 5a recommends D_m^m over D_m^w



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AAPM Medical Physics Practice Guideline 5a: Commissioning and QA of Treatment Planning Dose Calculations – Megavoltage Photon and Electron Beams, Appl. Clin. Med. Phys. 16 (2015).

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Opinions?

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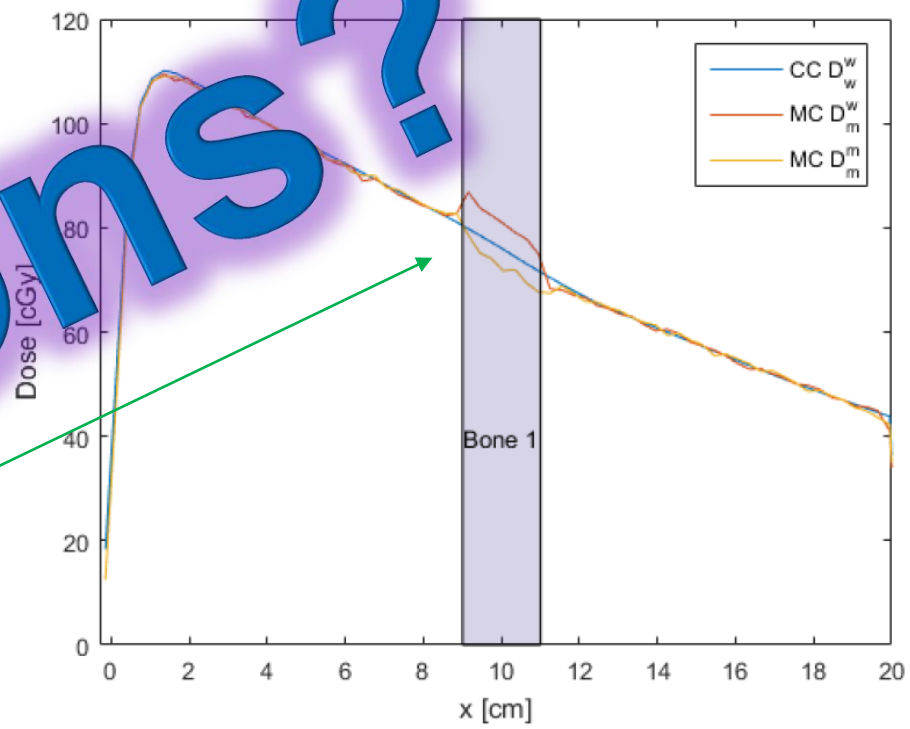

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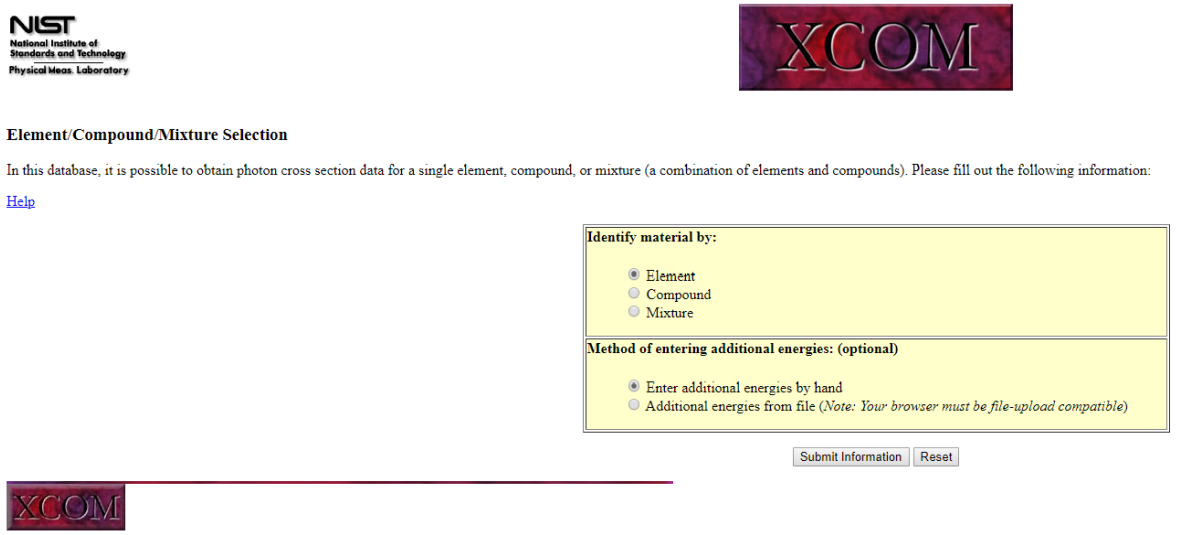
PHOTONS

- Total energy differential cross sections from NIST XCOM database
- Combined into RayStation Core and Interpolated materials (Interpolated in energy) according to the NIST XCOM instructions



https://www.nist.gov/pml/xcom-photon-cross-sections-database

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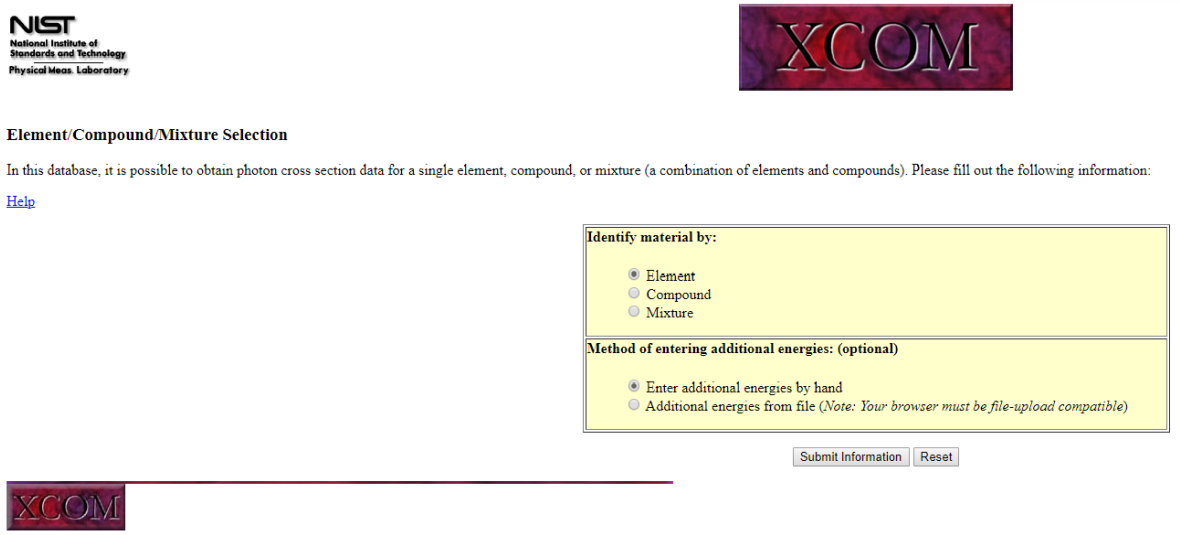
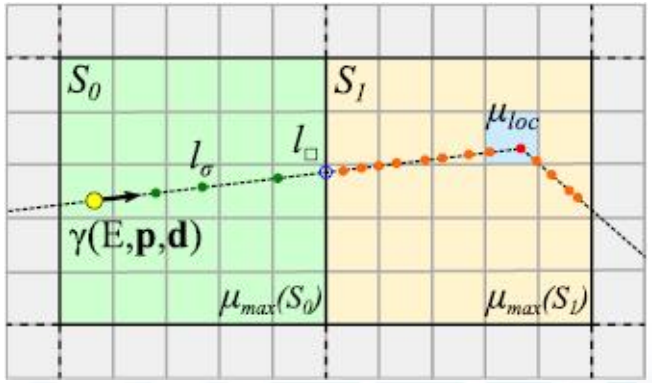


https://www.nist.gov/pml/xcom-photon-cross-sections-database

- Primary photons transported from sampled fluence positions to the edge of the dose grid
- To avoid traversing each voxel, Woodcock tracking (or fictitious cross section method) based on Von Neumann´s rejection technique is used



Behlouli et al. (2018), Improved Woodcock tracking on Monte Carlo simulations for medical applications; Phys Med Bio 63

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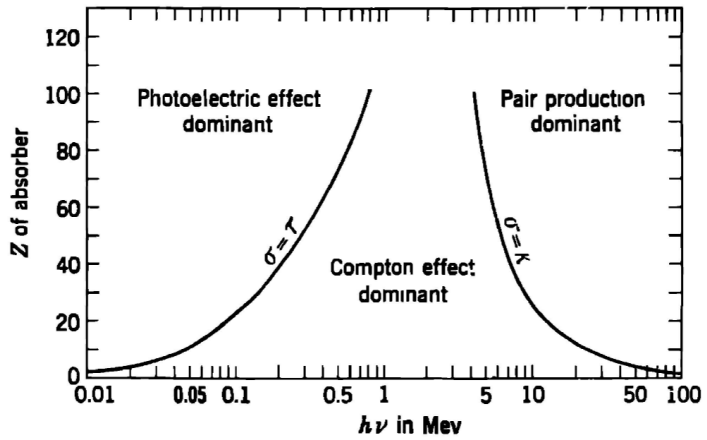
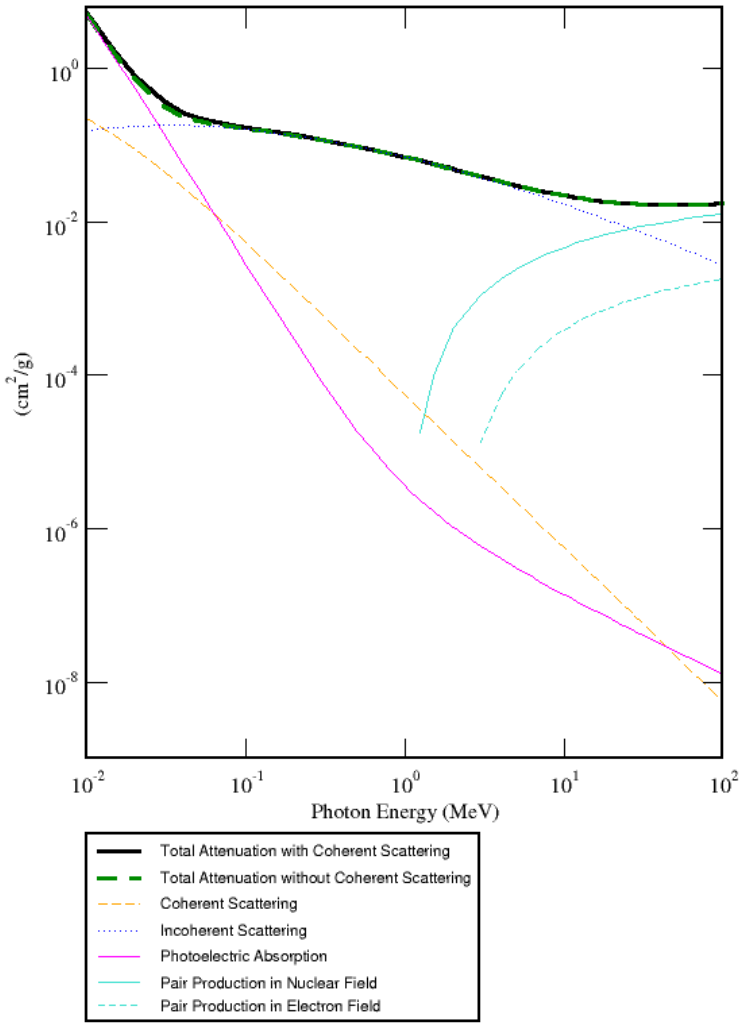
PHOTONS

- Compton scattering
- Photo-electric effect
- Pair production





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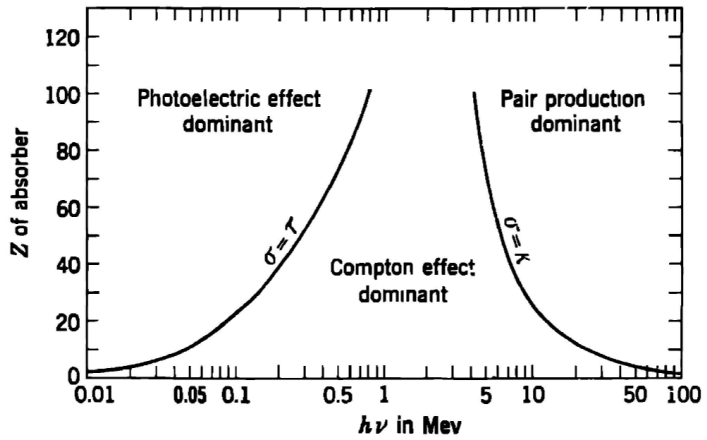
PHOTONS - COMPTON

- Compton scattering
  - Target electrons treated as free electrons
  - Differential cross-section given by K-N
  - Total Compton scattering cross section taken from NIST XCOM database



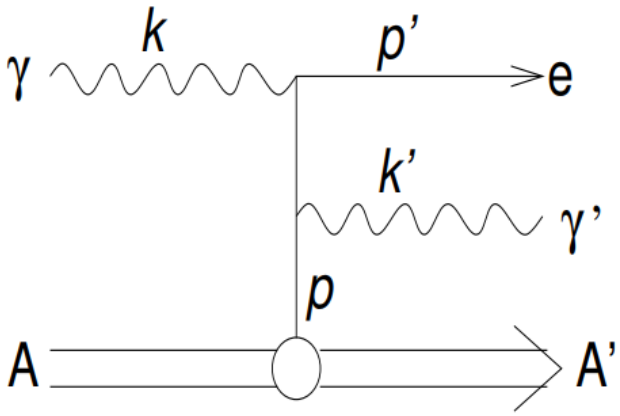


Figure 3: Feynman diagram for the Compton process

$$\frac{\mathrm{d}\sigma_{\mathrm{KN}}}{\mathrm{d}\cos\theta} = \pi r_0^2 Z \; X_{\mathrm{KN}} \; , \qquad X_{\mathrm{KN}} = \left(\frac{k_c}{k}\right)^2 \left[\frac{k_c}{k} + \frac{k}{k_c} - \sin^2\theta\right]$$

$$k_c = \frac{k}{1 + k(1 - \cos\theta)}$$

Kawrakow, IE. Mainegra-Hing, D.W.O. Rogers, F. Tessier and B.R.B. Walters, "The EGSnrc code system: Monte Carlo simulation of electron and photon transport," NRCReport No. PIRS-701, 2016.

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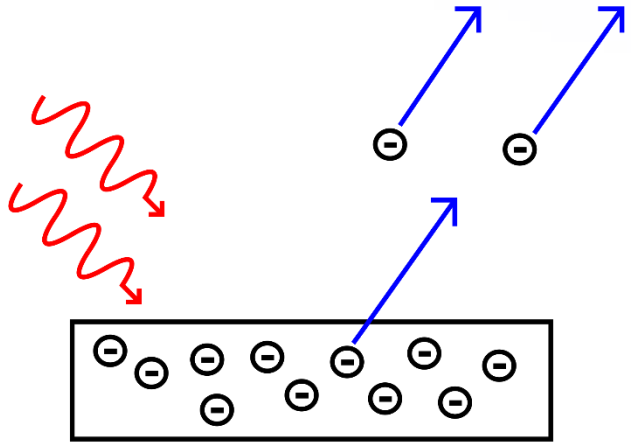
PHOTONS – PHOTOELECTRIC EFFECT

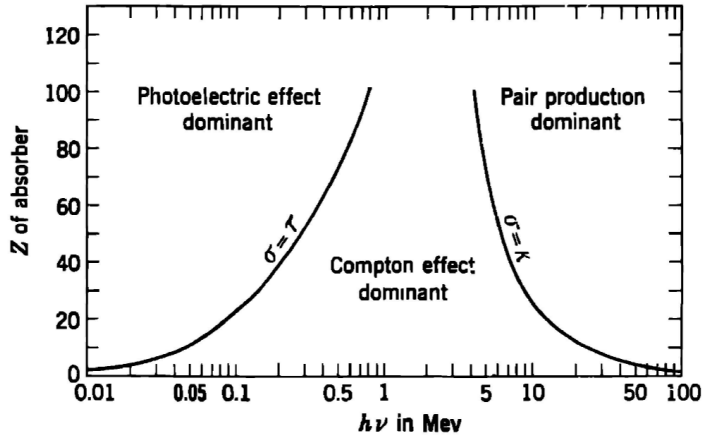
- Photoelectric effect
  - Electron with a kinetic energy = to the photon energy, if K> E_{cutoff}
  - If K< E_{cutoff}, energy deposited locally
  - Direction of the electron sampled from Sauter distribution



Picture from:
https://en.wikipedia.org/wiki/Photoelectric_effect

$$f(\mu)\mathrm{d}\mu = \frac{1-\mu^2}{(1-\beta\mu)^4}\left[1+\kappa(1-\beta\mu)\right]\mathrm{d}\mu$$

$$\kappa = \frac{\gamma}{2}(\gamma-1)(\gamma-2)\ , \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$



Kawrakow, IE. Mainegra-Hing, D.W.O. Rogers, F. Tessier and B.R.B. Walters, "The EGSnrc code system: Monte Carlo simulation of electron and photon transport," NRCReport No. PIRS-701, 2016.

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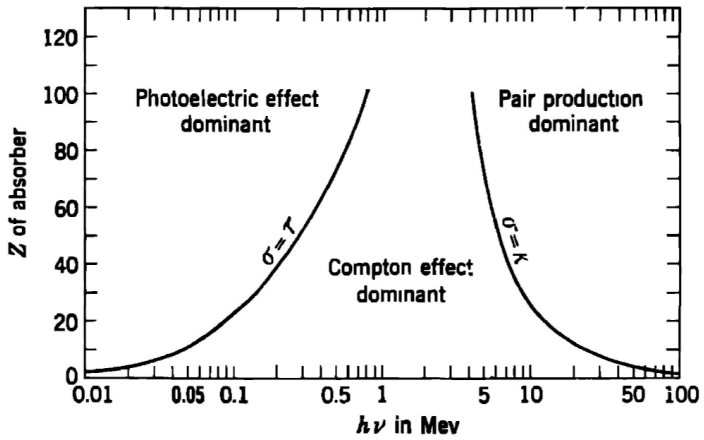
PHOTONS – PAIR PRODUCTION

- Pair production
  - Total cross-section = sum of pair creation cross sections in the nuclear field and electron field
  - ~~Triplet production ignored~~
  - Energy distributed randomly between electron and positron
  - Angular distribution sampled from the leading order term of the angular distribution



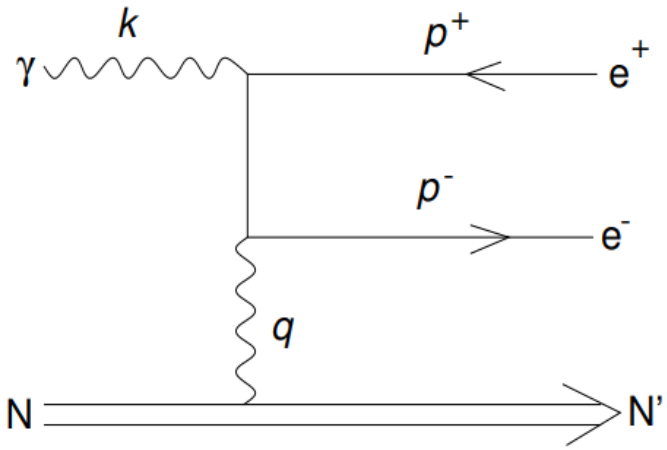


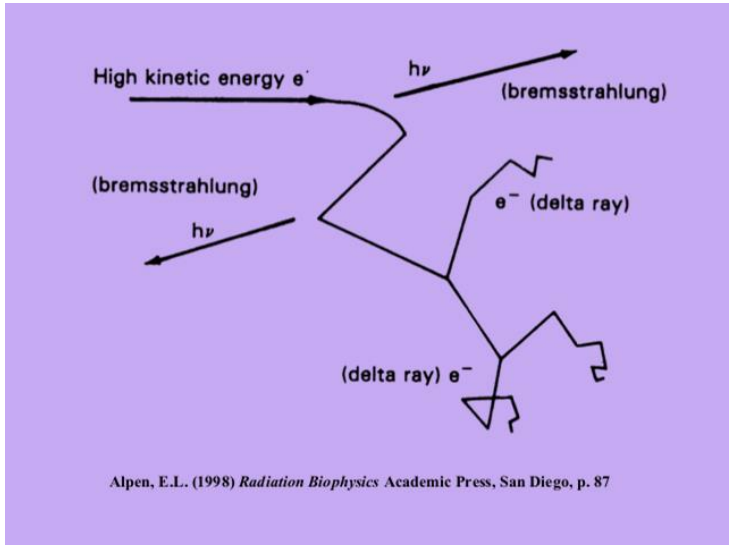
Figure 1: Feynman diagram for the pair production process

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_{\pm}} = N\frac{1}{(1-\beta_{\pm}\cos\theta_{\pm})^2}$$

Kawrakow, IE. Mainegra-Hing, D.W.O. Rogers, F. Tessier and B.R.B. Walters, "The EGSnrc code system: Monte Carlo simulation of electron and photon transport," NRCReport No. PIRS-701, 2016.

ELECTRONS

- Large number of interactions
- **MOST** only small difference in direction/energy → Condensed histories
- **SOME** large energy losses and changes in direction → Discrete interactions



Alpen, E.L. (1998) *Radiation Biophysics* Academic Press, San Diego, p. 87

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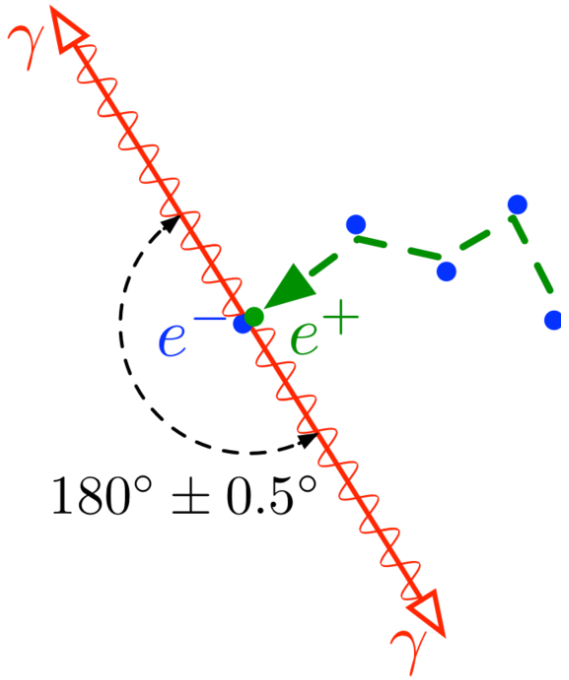
POSITRONS

- Treated as electrons +
- In-flight or at rest annihilation

$$\frac{d\sigma_{annih}}{dk} \xrightarrow{T \to 0} \infty$$

- Max cross section for T=400 KeV



Picture adapted from:
https://en.wikipedia.org/wiki/Electron%E2%80%93positron_annihilation

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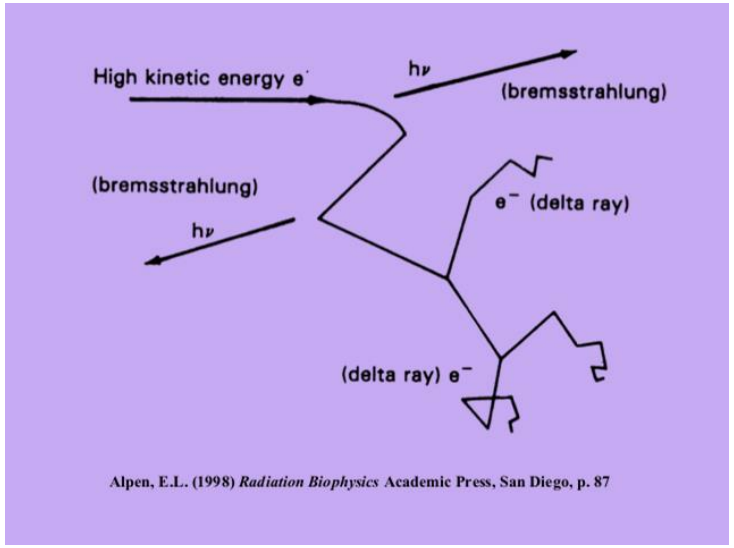
ELECTRONS - DISCRETE INTERACTIONS

- Discrete interactions
  - Moller scattering (e – e scattering)
  - Bremsstrahlung
- **Moller scattering**

- Binding effects ignored
- Threshold = 250 KeV (>> binding energies) ~ 0.6 mm range in water
- Energy and direction sampling as in egs manual

Kawrakow, IE. Mainegra-Hing, D.W.O. Rogers, F. Tessier and B.R.B. Walters, "The EGSnrc code system: Monte Carlo simulation of electron and photon transport," NRCReport No. PIRS-701, 2016.



- **Bremsstrahlung**

- Radiative stopping power from NIST ESTAR for each material
- Initial electron only loose energy and does not change direction
- Photon direction: $\theta = \frac{m_e}{m_e + T}$
- Photon energies sampling as in egs manual

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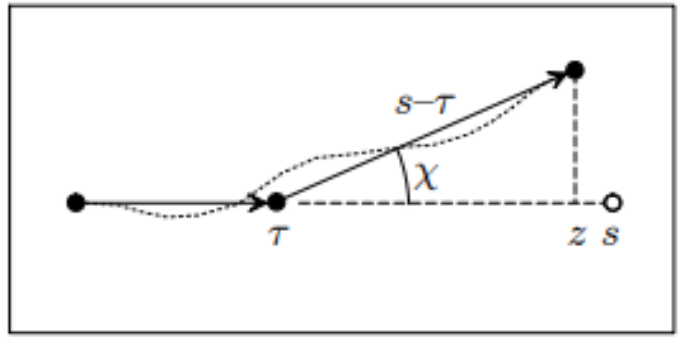
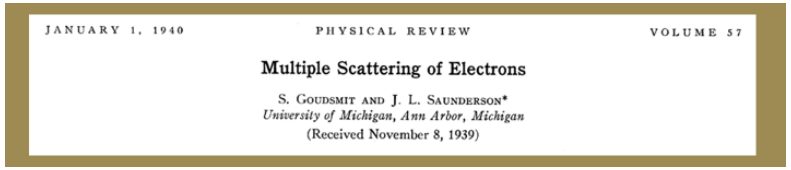
ELECTRONS, MCS

- Angular deflection sampled from angle probability distribution calculated with **Goudsmit-Saunderson** theory
  - Simple and fast sampling method
  - egsnrc, VMC++
  - No small angle approximation

- Random hinge steps





JANUARY 1, 1940 PHYSICAL REVIEW VOLUME 57

Multiple Scattering of Electrons

S. GOUDSMIT AND J. L. SAUNDERSON*
University of Michigan, Ann Arbor, Michigan
(Received November 8, 1939)

*It is possible to write the **scattering probability** as a series in Legendre polynomials*

$$f(\theta)=\frac{1}{4\pi}\sum(2l+1)G_l P_l(\cos\theta)$$

The approximate Gaussian behavior for small angles is NOT used in RayStation (NO small angle approximation)

S.A. Goudsmit and J.L. Sauderson, Phys Rev., 57 and 58 (1940)

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RANDOM HINGE

- MCS → evaluated ONCE per Random hinge
  - Two straight legs connected by a hinge point
  - A hinge leg may extend over multiple voxels
  - Deflection due to Multiple scattering at the hinge point
  - Length of the random hinge is the smallest between:
    - Distance to the next discrete interaction
    - 15% of the kinetic energy
    - 500 KeV

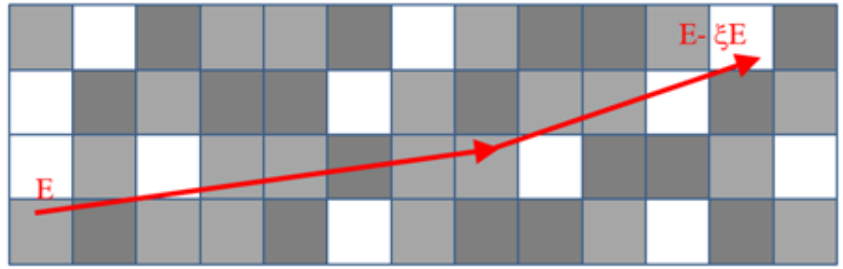

Figure 44. A random hinge step with two legs for a proton with energy E_i at the beginning of the step and losing energy $\Delta E = \xi E_i$ after the step. The deflection due to multiple scattering is applied at the hinge point.

- E_{cut}^{RH} =250 KeV
- E<250 KeV (~ 0.6 mm range in water), no MCS considered

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COLLISION STOPPING POWER

- ICRU 37

$$S_{col} = 2\pi r_e^2 \rho_e mc^2 \frac{1}{\beta^2} \left[\ln(T/I)^2 + \ln(1+\tau/2) + F^-(\tau) - \delta\right] \quad \text{[Eq. 47]}$$

where

$$F^-(\tau) = (1-\beta^2)[1 + \tau^2/8 - (2\tau+1)\ln 2] \quad \text{[Eq. 48]}$$

ρ is the mass density, ρ_e the electron density, r_e the classical electron radius, T the kinetic energy and τ the kinetic energy in terms of electron masses (T/m_e).

- One part of the collision stopping power, with energy transfers larger than the threshold, is accounted for in the Moller scattering
- The remaining part is the restricted stopping power (*L*)
- The energy loss over a voxel = integrating the restricting stopping power in the local density and medium

$$\Delta E \approx \frac{s\,(L\,(E_0) + L\,(E_0 - sL\,(E_0)))}{2} \quad \text{[Eq. 49]}$$

where s is the geometric distance, L the restricted stopping power and E_0 the initial energy of the electron.

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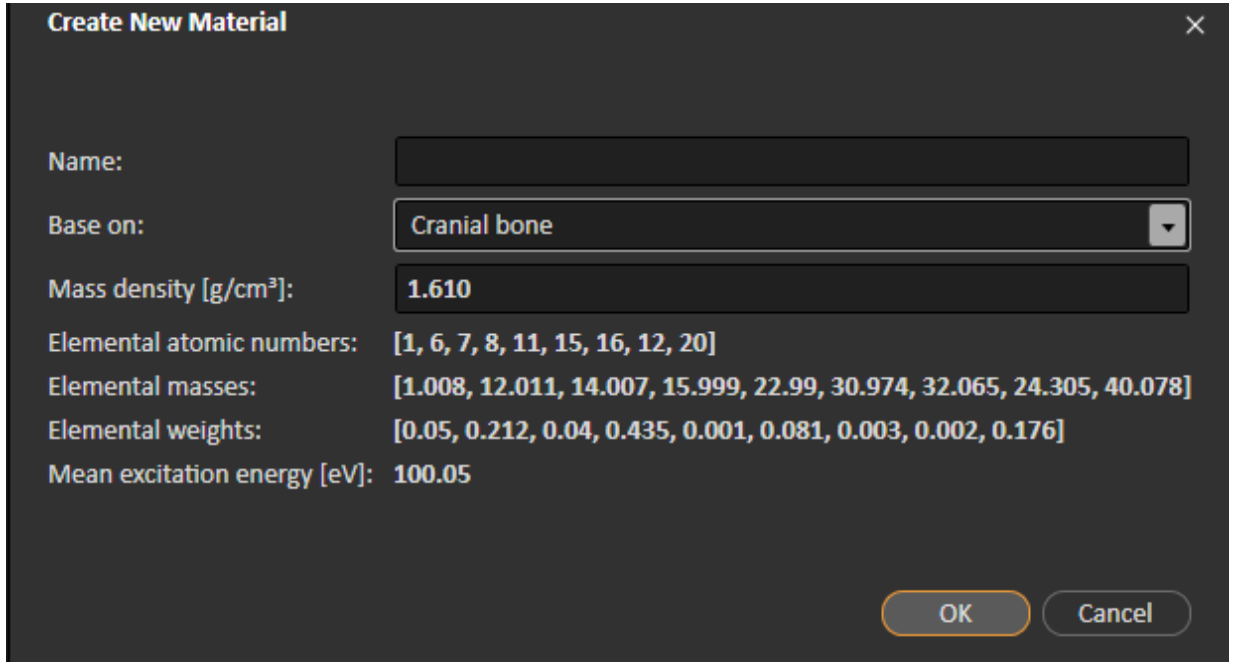
CUTOFFS

- Production cutoffs
  - Electrons: 250 keV (<1mm range in water)
  - Photons: 50 keV
- No multiple scattering below 250keV
- Transportation cutoffs
  - None
  - Particles transported until 0 energy or outside the volume

MATERIAL HANDLING

- Supports all materials
- Defined by composition, density and mean excitation energy
- Cross sections and stopping power from material composition
- HU → mass density → material assignment
  - Like ions and electrons



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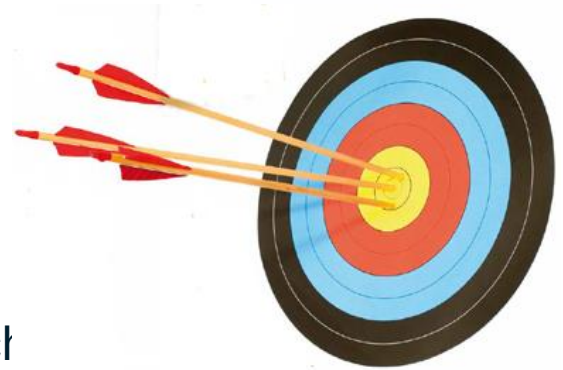
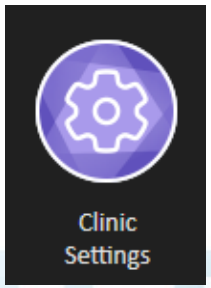
STATISTICAL UNCERTAINTY

Statistical error



- Independent batches
- Statistical error x voxel = Dose variance of the dose per voxel over all batcl
- More and more batches, the longer it computes → estimated variance is more and more accurate
- Statistical error per fraction

  → Mean of 1 standard deviation error over all voxels with dose > 50% of the maximum dose
- The lower dose voxels will not be used to estimate the uncertainty but the uncertainty in the low dose voxel can be estimated to equal or lower than the high dose voxels
- **Clinical dose** if statistical error < threshold value (user-defined)



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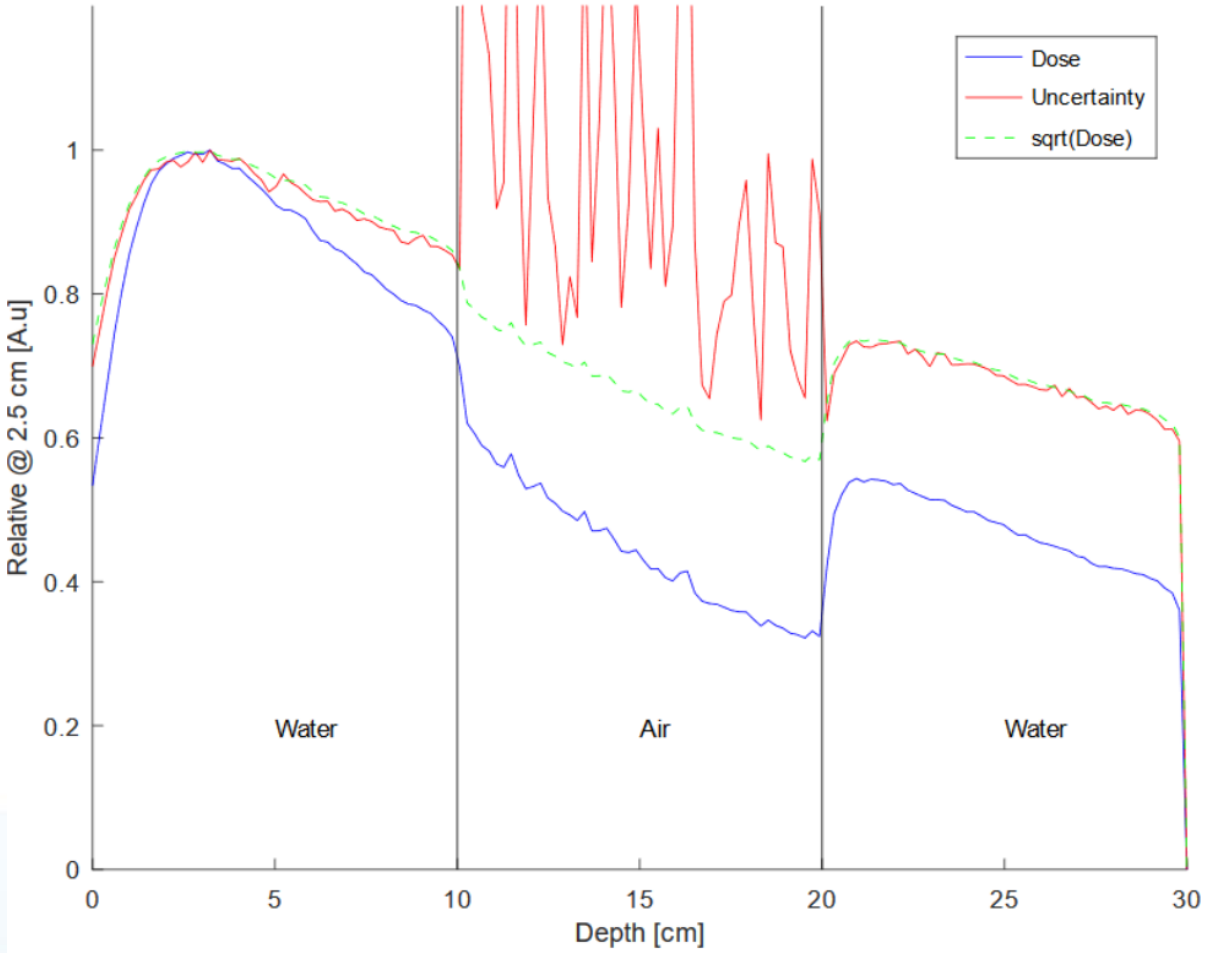
STATISTICAL UNCERTAINTY



- For voxels with similar density, the uncertainty is proportional to the square root of the dose.
- Low dose voxel have lower uncertainty than high dose voxels in absolute dose
- Low dose voxel have higher uncertainty relative to voxels than higher dose voxels

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DIFFERENCES TO CC

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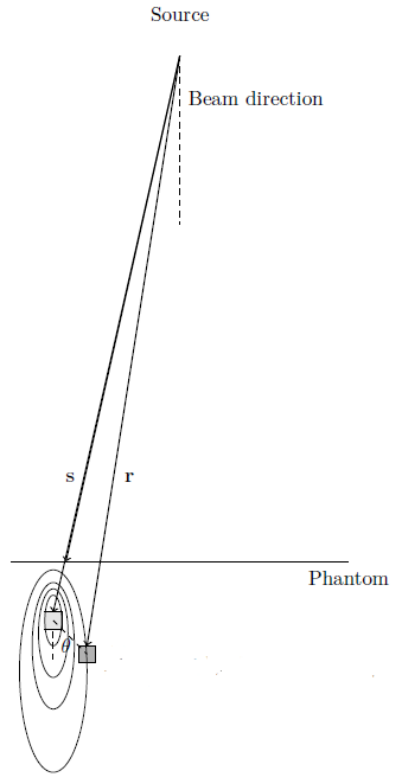
NO-KERNEL TILT APPROXIMATION IN THE CC

- Approximation in CC
- All kernels parallel to beam direction
- More dose on central axis

→ Differences in the penumbra and out of field regions compared to the Monte Carlo dose engine



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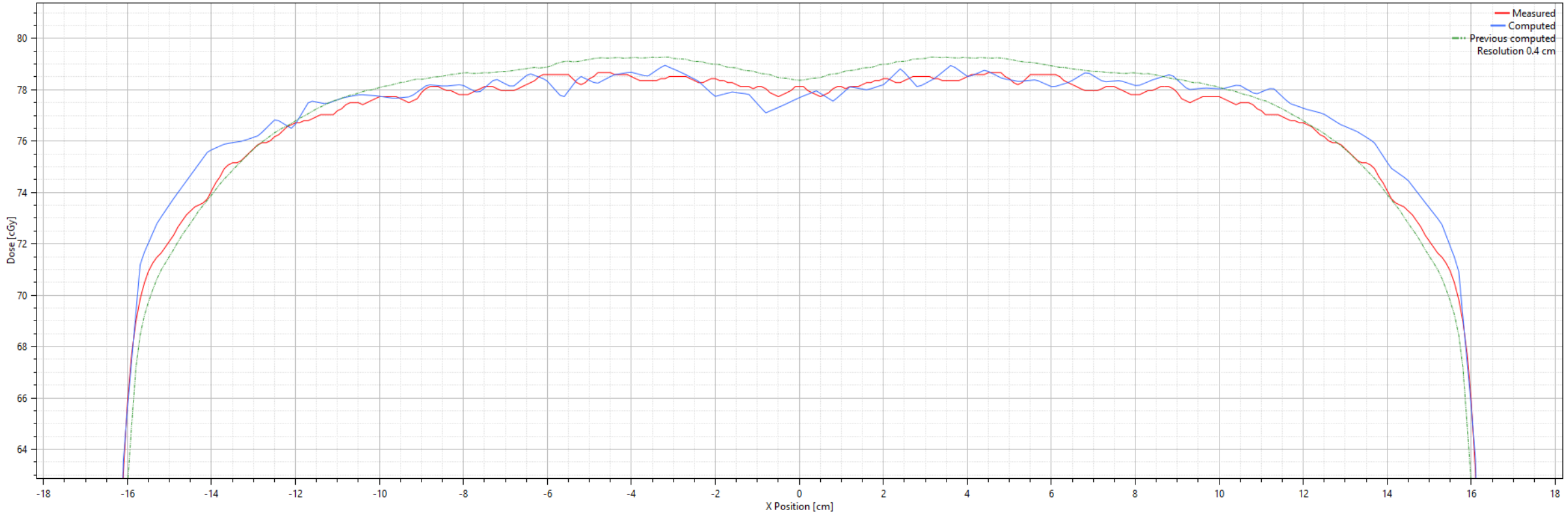
PROFILES

30x30 X-profile, 10cm depth (blue – MC, green – CC)



- **FF Source** parameters

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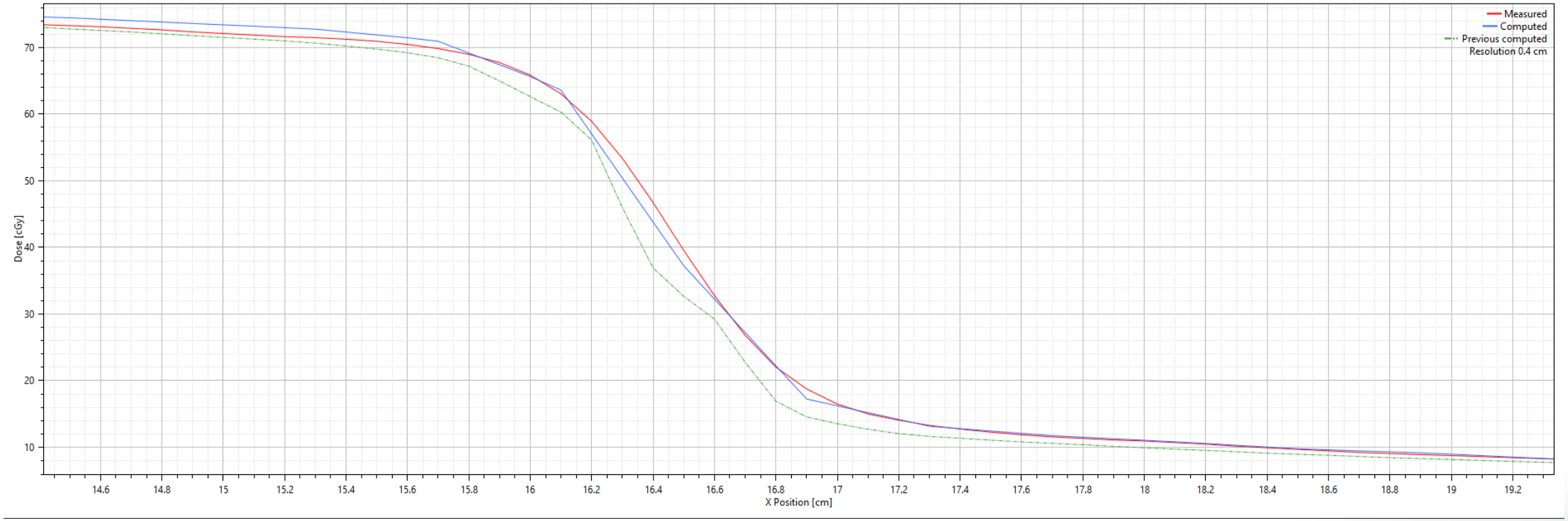
PENUMBRA

30x30 X-profile, 10cm depth (blue – MC, green – CC)



- **Primary Source** parameters
- **Collimator Calibration parameters** can be different: start the MC modelling with collimator calibration parameters = 0

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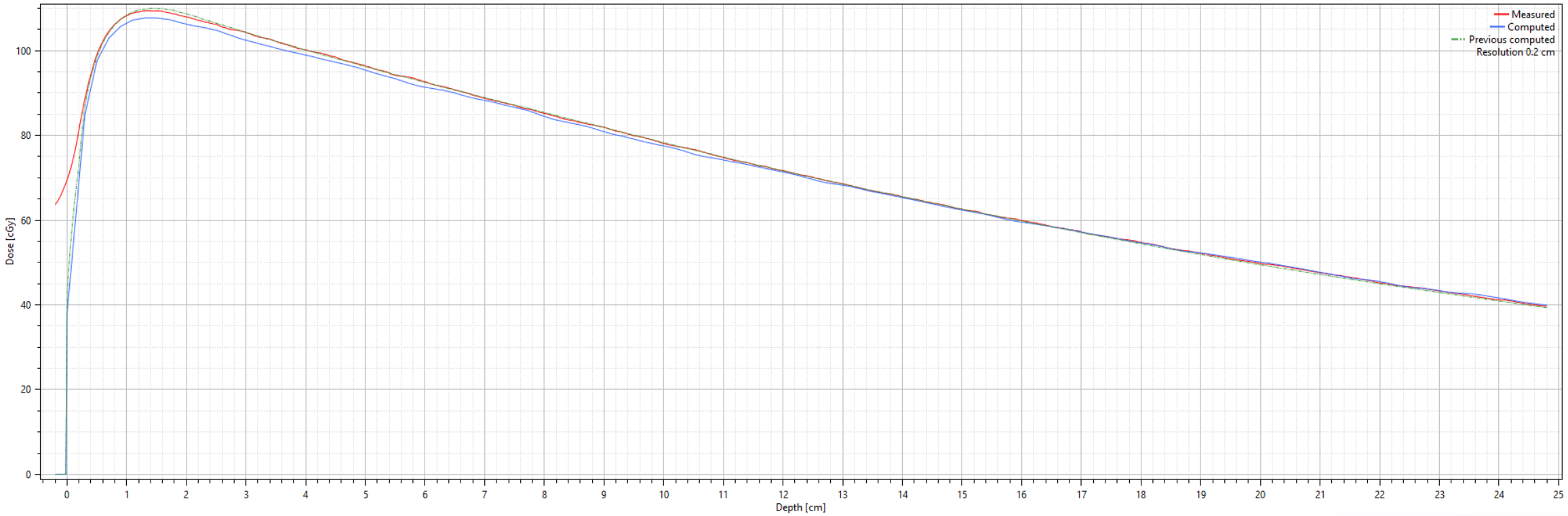
DEPTH DOSES

30x30 field (blue – MC, green – CC)



- **Photon Energy spectrum**
- **Electron parameters**

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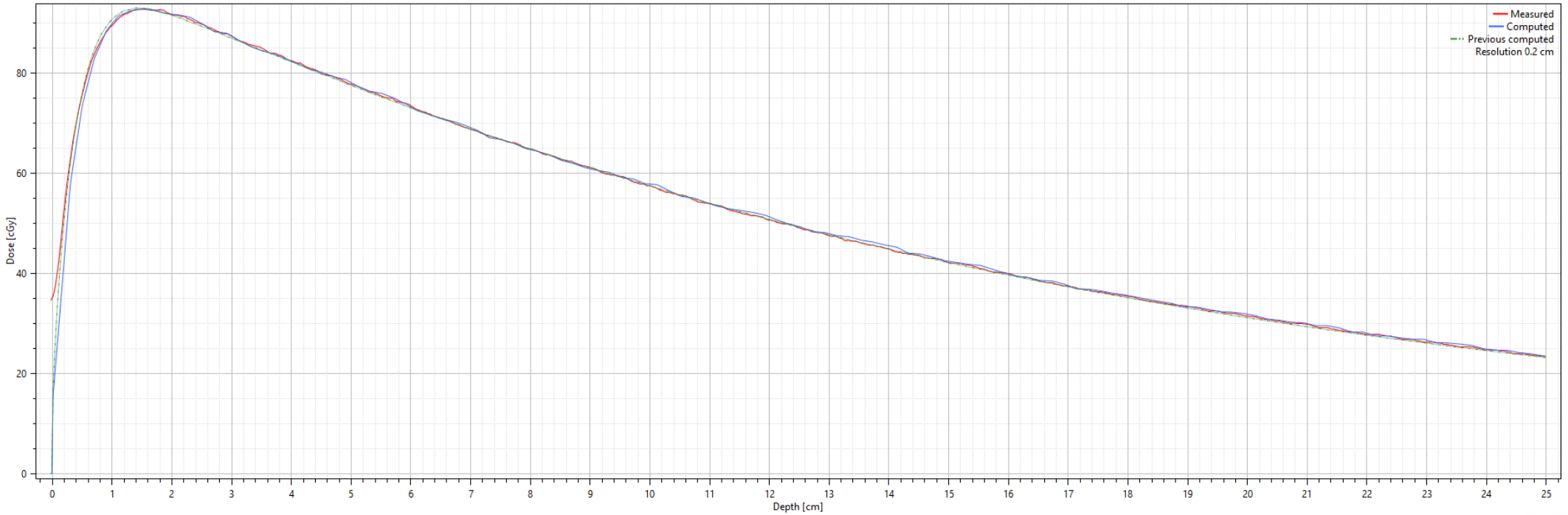
DEPTH DOSES, CONTINUED

3x3 field (blue – MC, green – CC)



- **Overall normalization value**
- **OFC**

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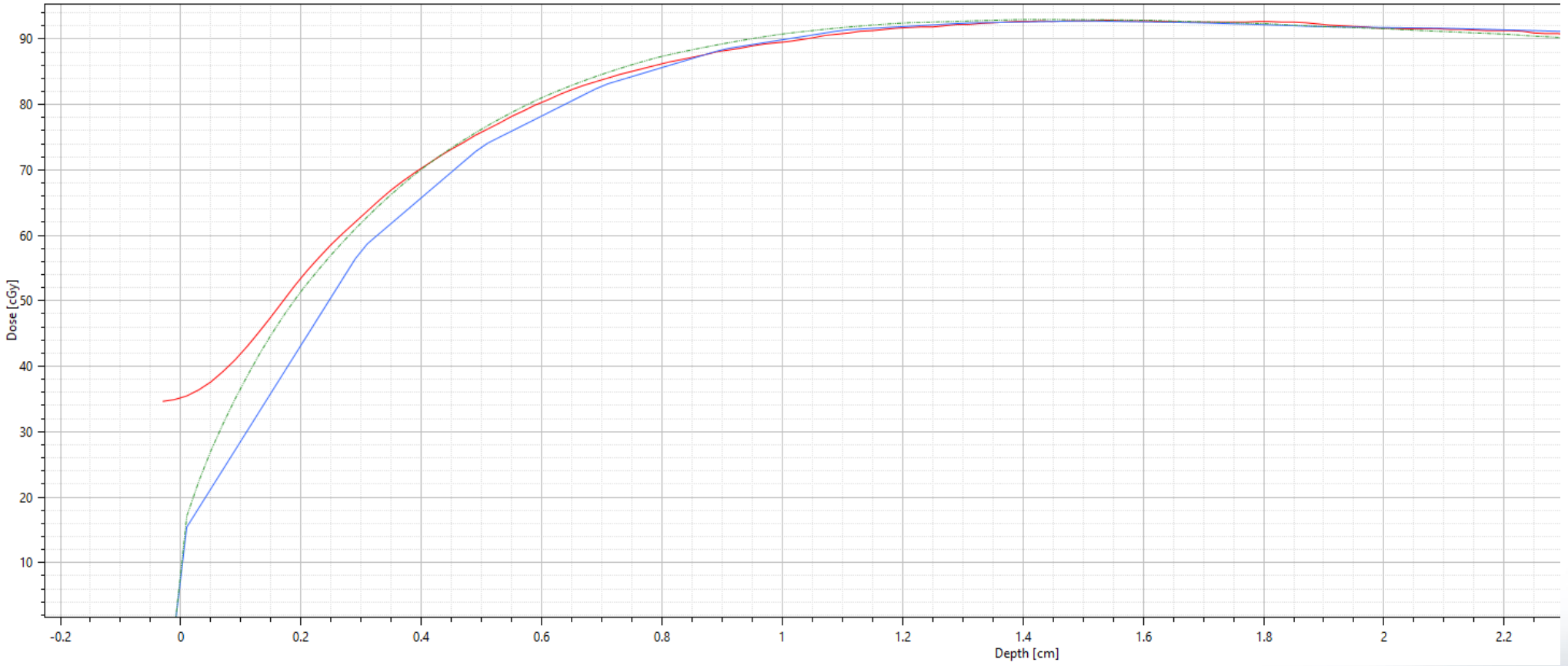
CC PRE-CALCULATED KERNELS

- Computed in infinite water (almost)
- Good approximation in homogeneous regions

→ Differences in the build-up region compared to the Monte Carlo dose engine

SURFACE DOSE

3x3 field (blue – MC, green – CC), zoomed in at surface



- **Photon Energy spectrum**
- **Electron parameters**

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COMPUTATION TIME

- Increased with
  - Lower uncertainty sigma~1/sqrt(n), ie half the uncertainty -> 4 times longer
  - Smaller voxels
  - Larger dose grids
  - Larger targets
- Unaffected by
  - Number of beams

- On fast GPU
  - IMRT plan 1% uncertainty, 3mm voxels ~5s
  - Dual arc plan 1% uncertainty, 2mm voxels ~15s

NEW IN 10A AND LATER VERSIONS

- The random number generator was changed from 9B to 10A.
- Machines from 9B or earlier **do not need** recommissioning.
- The difference is negligible with low uncertainty, but can be higher with higher uncertainty.
- Reason for changing random number generator was because the old one was not sufficient for proton MC (which is introduced in 10A), and it was decided to use the same random number generator for both photons and protons.

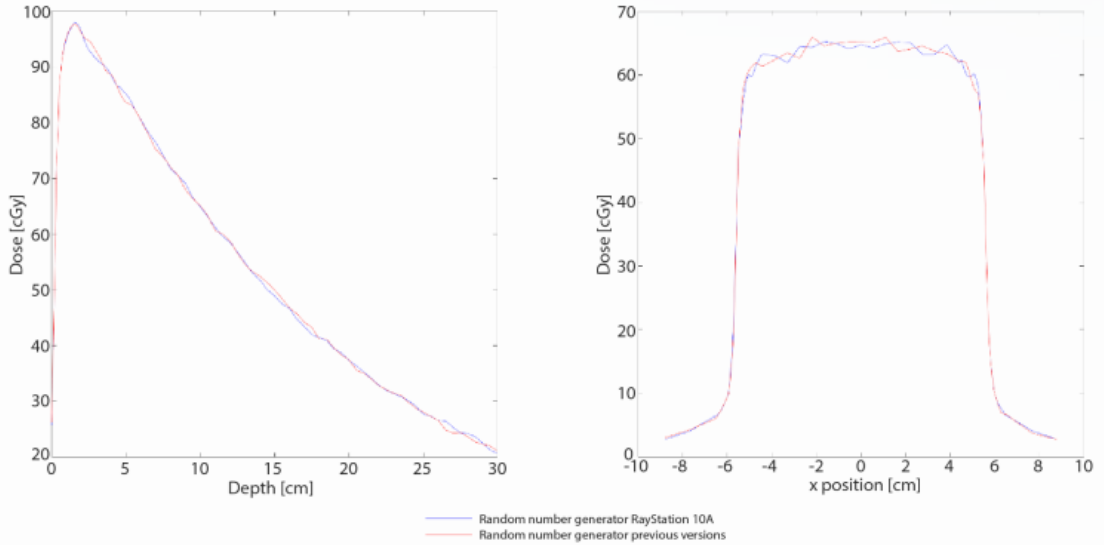

Figure 1. Dose curves computed with uncertainty 2%. Curves for the random number generator in RayStation 10A are shown in blue, and for previous versions in red. The curves to the left show dose related to depth, and to the right dose related to x-position.

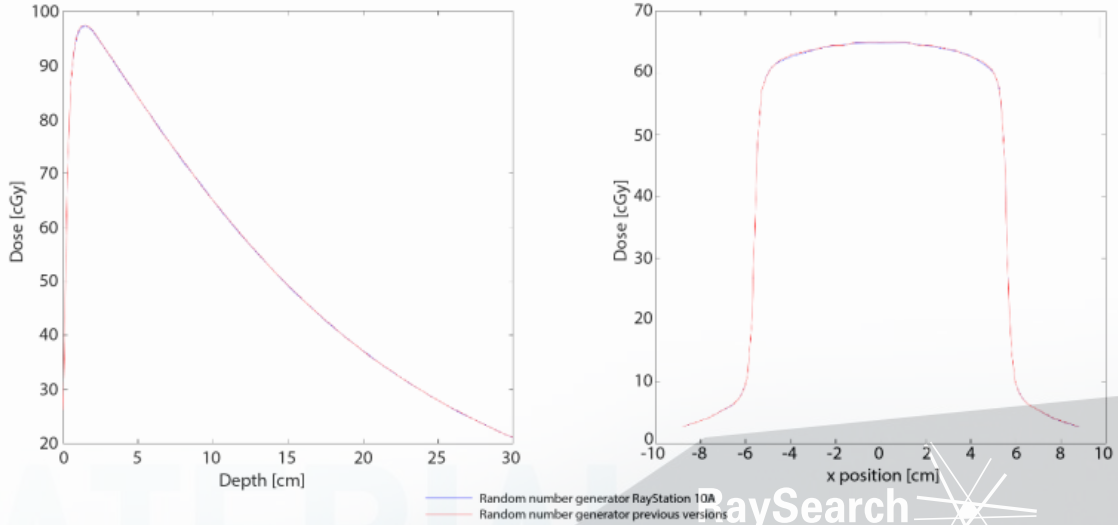

Figure 2. Dose curves computed with uncertainty 0.2%. Curves for the random number generator in RayStation 10A are shown in blue, and for previous versions in red. The curves to the left show dose related to depth, and to the right dose related to x-position.

THANK YOU!

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