Introduction to Monaco 5 algorithms

Monaco Physics Level 1 Course

GPS- Physics

ELEKTA

Objectives

After this session the student will:

1. Know the fundamentals of the three algorithms implemented in Monaco 5

Overview of Topics

- Monaco 5 algorithms and delivery modes
- Photon Monte Carlo algorithm
- Photon Collapsed Cone algorithm
- Electron Monte Carlo algorithm

Delivery modes

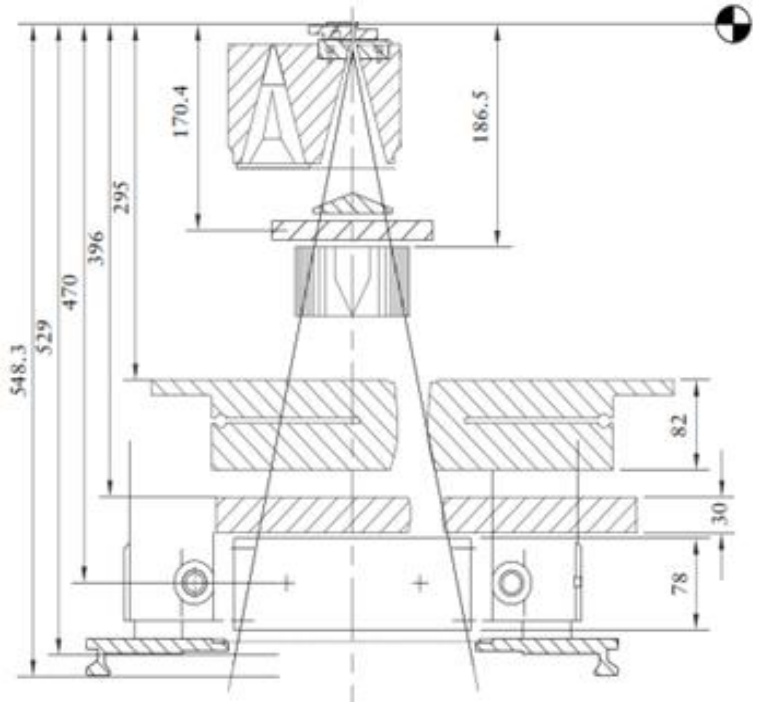
Algorithm	Description	Delivery modes supported
Photon : Monte Carlo	Based on XVMC (X-Ray Voxel Monte Carlo) An accurate method for the calculation of dose distributions for treatment planning (~1% compared to EGS)	3D 3D Static Arc Conformal RT dMLC Dynamic Conformal Arc Step & Shoot IMRT VMAT mArc (VMAT for Siemens)
Photon : Collapsed Cone	Fluence based algorithm	3D
Photon : Pencil Beam	Finite Size Pencil Beam (FSPB) Designed for Beamlet-based IMRT optimization **** Not used for final dose calculation****	3D 3D Static Arc Conformal RT dMLC Dynamic Conformal Arc Step & Shoot IMRT VMAT mArc (VMAT for Siemens)
Electron : Monte Carlo	Coupled multisource phase space engine using VMC++ to calculate deposited dose	3D

Overview of Photon Monte Carlo algorithm

- Photon Monte Carlo algorithm
- General description
- Fluence engine
- MLC/Jaw modeling
- MC dose calculation
- Usage of measured data for pMC modeling

General description

Model of the treatment head



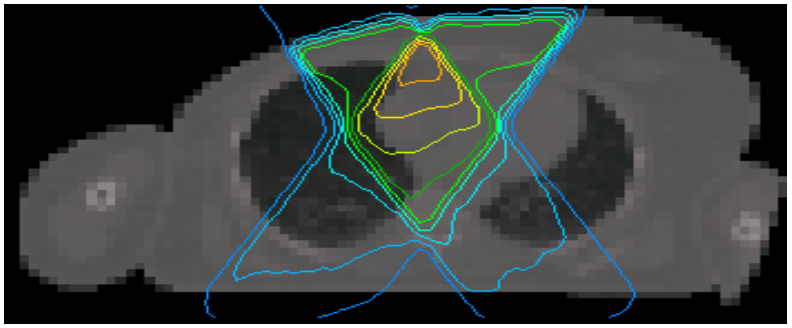
Fluence engine

Based on analytical source models

Model of MLC and Jaw

Transmission Filters

CT model of the patient



Dose engine

MC calculation starts at the patient surface by using the particles created by the Fluence engine

Photon Monte Carlo algorithm

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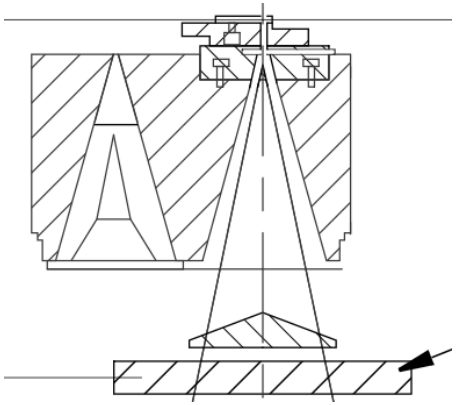
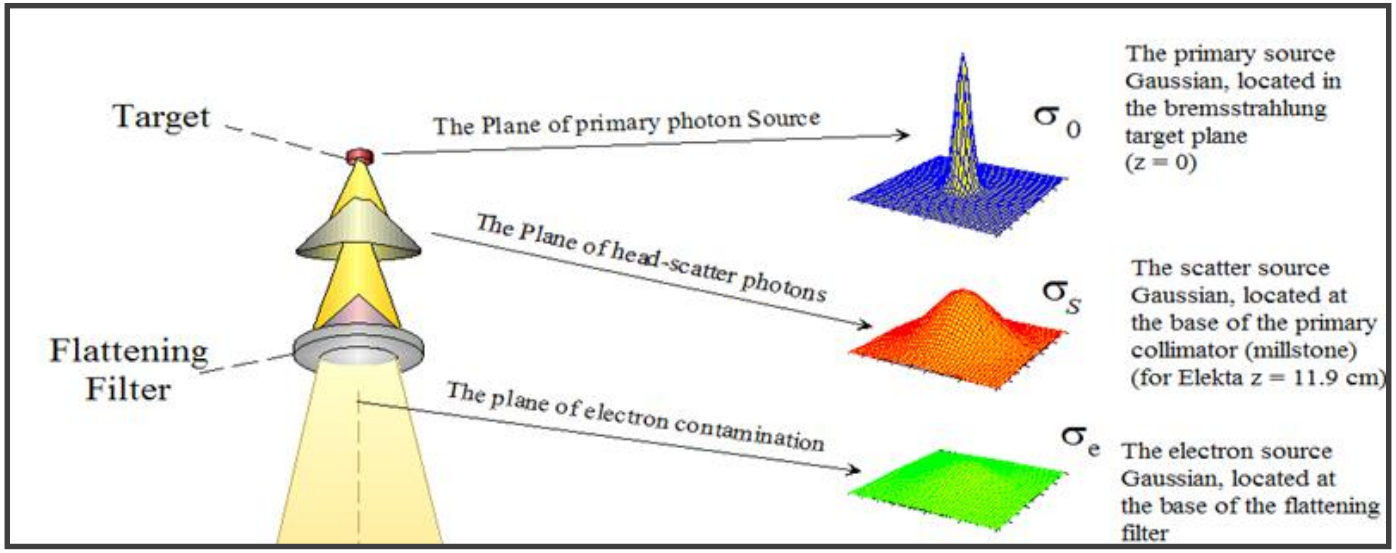
Fluence engine



Linac head is modeled as three different sources (Virtual Source Model, VSM):

1. Primay photons
2. Secondary photons
3. Electron contamination



Photon Monte Carlo algorithm

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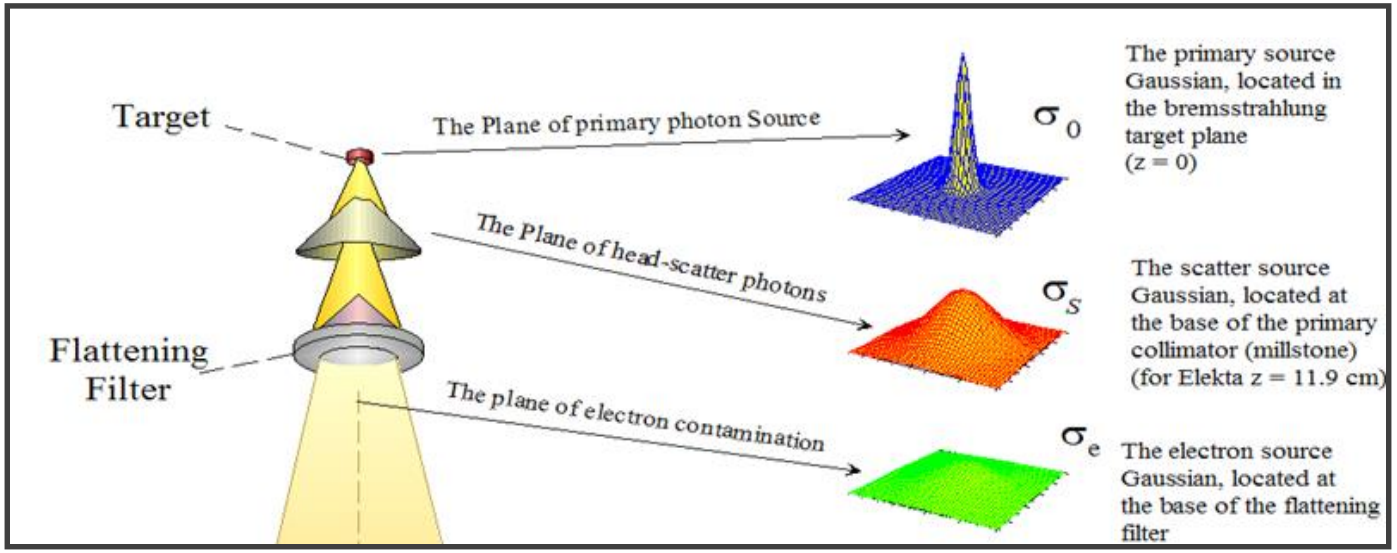
Fluence engine



The energy distribution and geometry are characterized by analytical functions.

The functions until the calculated

dose matches measured dose within acceptance range. modeling process consists on adjusting the parameters of those analytical

Fluence engine

There is a Flattening Filter model implemented, also with parameters that can be adjusted (to account for FFF cases for example), but still without using Monte Carlo calculations.

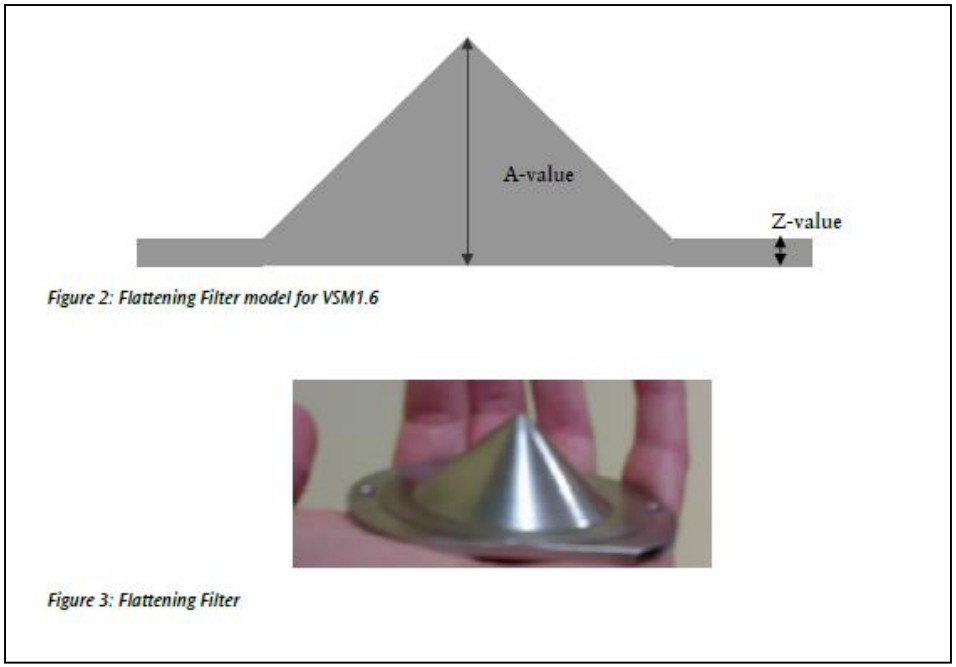
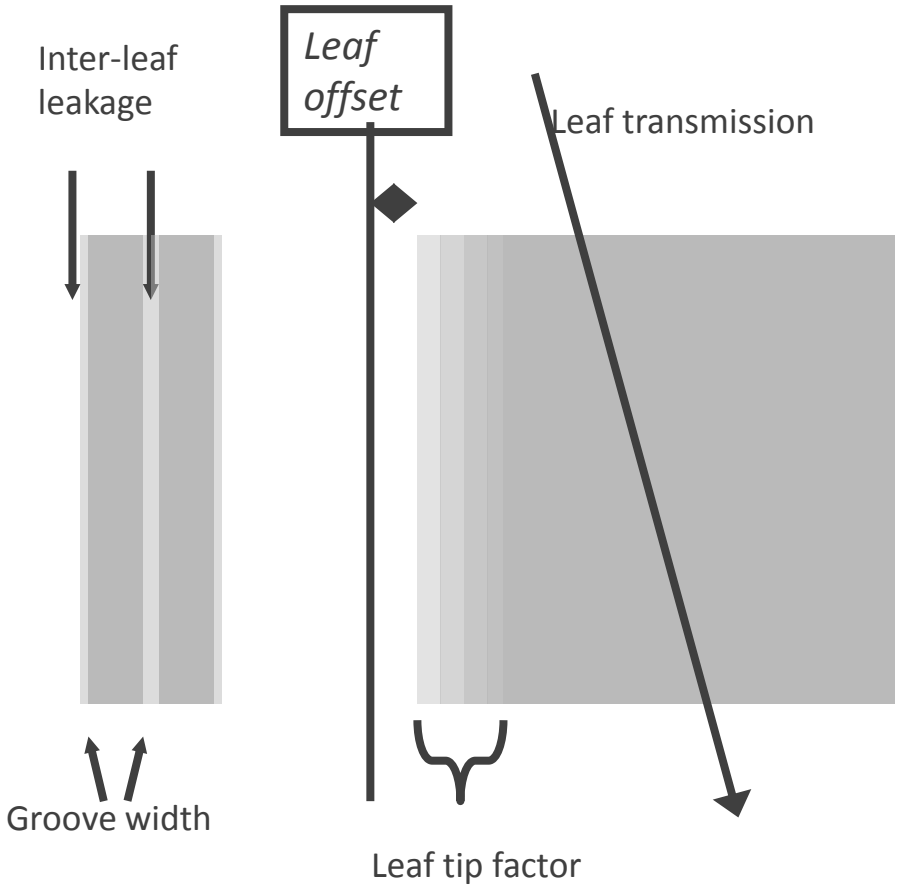


Figure 2: Flattening Filter model for VSM1.6

Figure 3: Flattening Filter

MLC/Jaw modeling

- MLC/Jaws are modeled via a transmission filter. Transmissions, groove and tip effect are taking into account.
- MLC parameters are model specific and are editable by the user, to optimize the matching between Monaco calculation and actual MLC behavior.
- There is no particle transport through MLC/Jaw, so no energy or direction change.



MC dose calculation

- First, dose is computed in the voxel. Dose is computed as the average dose from the contribution from each particle in given voxel

$$D_k = \frac{1}{N}\sum_{i=1}^{N} d_{i,k}, \quad \text{Where:}$$

Index k indicates voxel
Index i indicates photon

- The system also computes differences from individual particles doses and average dose and get statistical uncertainty, as the sum of the squared differences from the average voxel dose.
- Statistical uncertainty plays a major role, and is determined by the number of photon and electron histories.

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}\left(d_{i,k} - D_k\right)^2$$

$$Variance = \sqrt{\sigma^2/(N-1)}$$

- Note the square root behavior of variance; to get twice the accuracy requires 4 times the work.
- Full Monte Carlo Simulation is still too time consuming.
- Variance reduction techniques (VRT) are common.

ICCR benchmark criteria

MC dose calculation

The general history density equation in Monaco is as follows:

$$HD = C / (S * \{\sqrt[3]{vv} / 3\})^2$$

Where:

C: empirical constant

vv: voxel volume

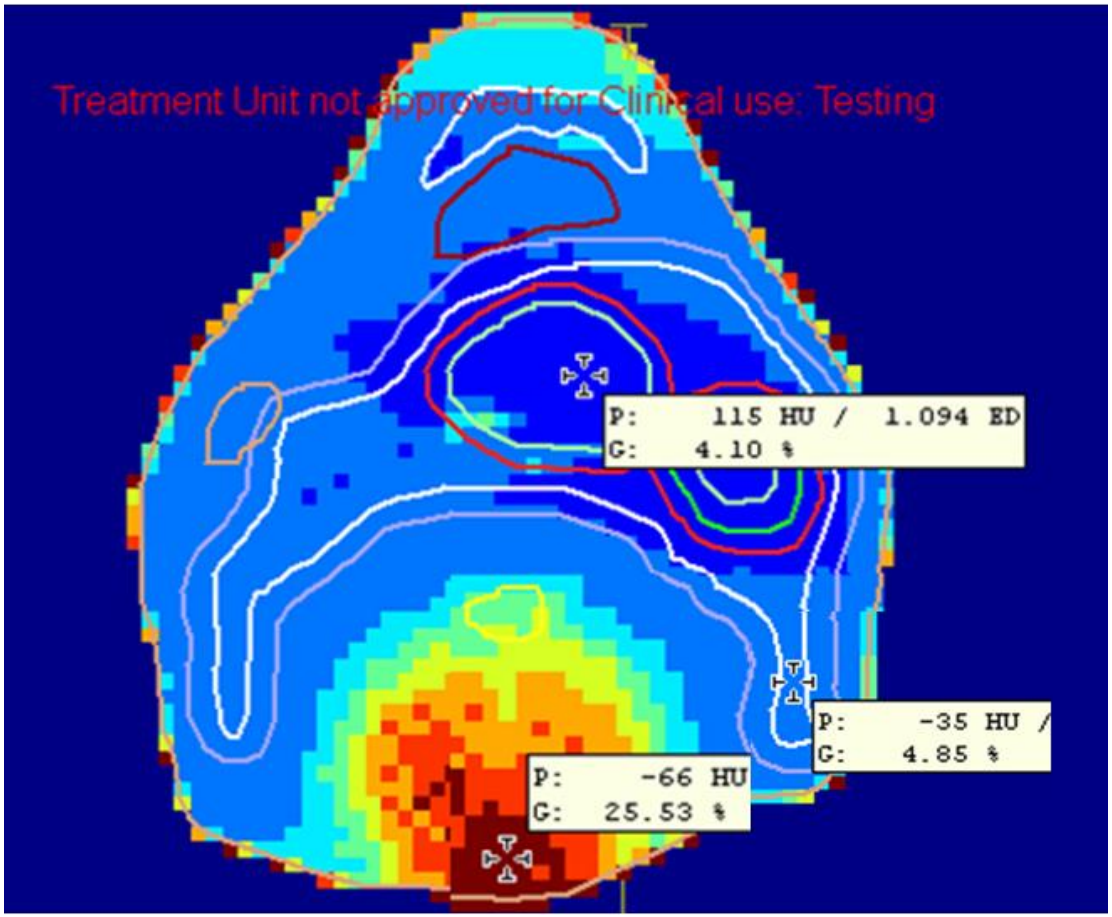
HD: history density (part/mm^2)

S: user supplied uncertainty

As it can be observed, reducing the voxel size will make the HD to increase, so that the statistical uncertainty is kept around the same value (this makes negligible the MC-TPS typical voxel size effect of increasing the uncertainty when reducing the voxel size, since Monaco will increase the history density according to the voxel size decrement).

MC dose calculation

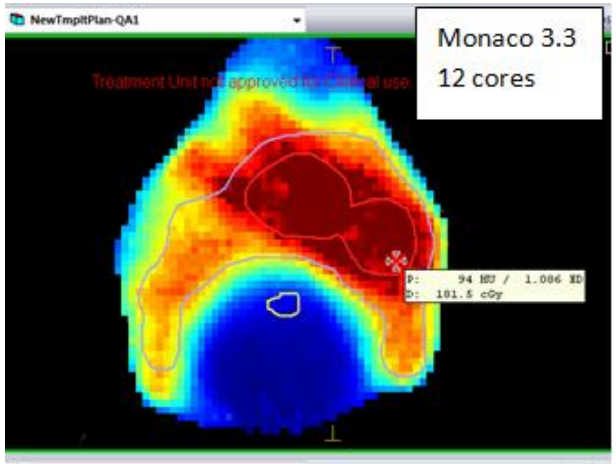
The statistical uncertainty set by the user applies on 90% dose regions (with density close to 1). For lower dose regions or lower RED, the uncertainty will be higher:

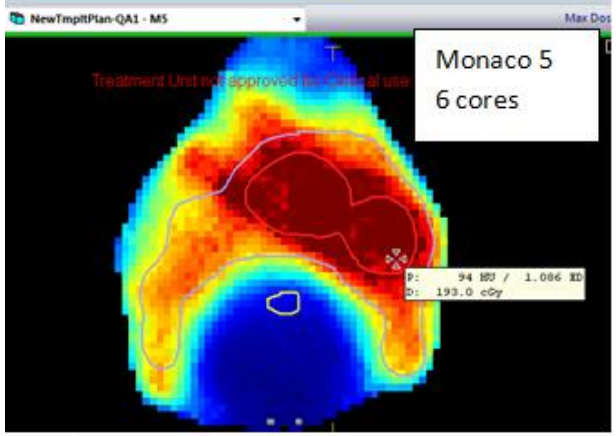


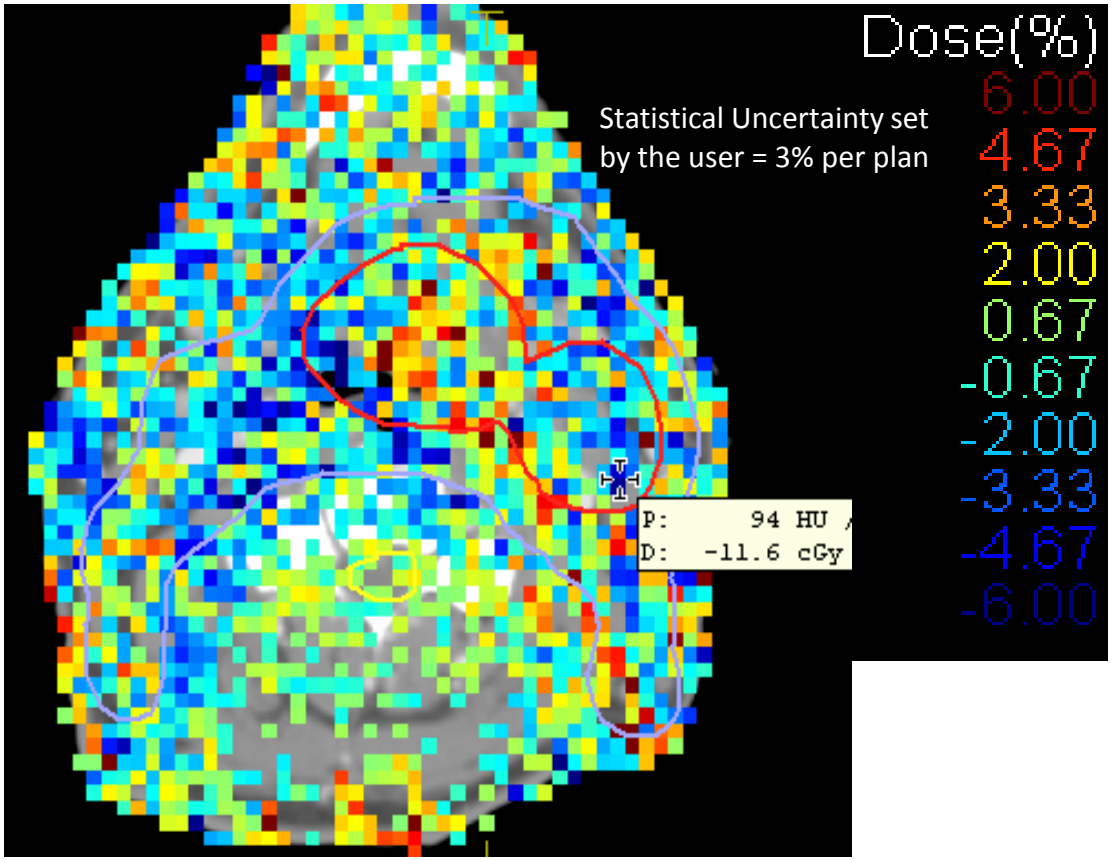
MC dose calculation

The seed used for random number generation is fixed in Monaco, so that one particular calculation repeated several times in one particular computer will lead to the same result.

However, the same calculation done in different harwares (different # cores) will lead to different results, since the random numbers used at every step of the calculation will be different







Photon Monte Carlo algorithm

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Exercise: MC statistical uncertainty

- Open Monaco -> QA Clinic -> Monaco Phantom
- Create a 3D plan: TU-SampleEk80, 5x5cm, SSD=90, 100MU
  - CASE1
  - Force all RED=1
  - Voxel size = 0.3cm, Statist.Uncer. Per CP = 1%
  - Write down: Statistical Uncertainty @ Iso, # histories, Total Dose @ Iso, Mean Dose @ Iso (radius = 0.3cm)
  - Compare the statistical uncertainty @ 10cm against 15cm
  - CASE2
  - Run the same calculation changing the Statis.Uncer. Per CP to 2%
  - Compare the Statistical Uncertainty @ Iso, # histories, TD @ Iso, MD @ Iso (radius 0.3cm) with the previous calculation

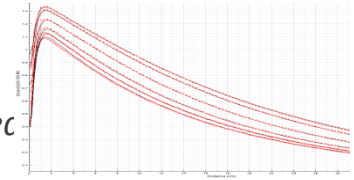
Exercise: MC statistical uncertainty

- Open Monaco -> QA Clinic -> Monaco Phantom
- Create a 3D plan: TU-SampleEk80, 5x5cm, SSD=90, 100MU
  - CASE3
  - Repeat the last calculation by forcing the RED = 0.5. Compare the Statistical uncertainty @ ISO and the # histories.
  - CASE4
  - Put back the RED = 1 and re-calculate. Compare the Statis.Uncert. @ Iso, TD @ Iso and MD @ Iso (radius 0.3cm)
  - CASE5
  - Repeat the previous calculation (RED=1, Statistical Uncertainty = 2% per CP) changing the voxel size to 5mm

Usage of measured data for pMC modeling

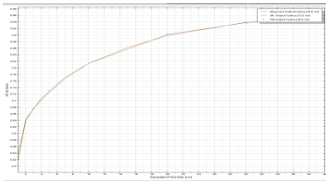
Spectrum

Spectrum parameters are adjusted by comparing measured PDDs to calculated PDDs



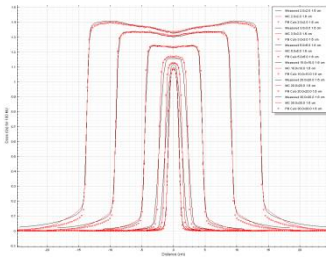
Primary/Secondary/Electron component weights

Component weights are adjusted mainly looking at the OF



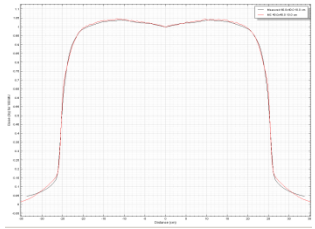
Sources geometry parameters

Geometry parameters such as sources sizes, are mostly determined by optimizing the measured and calculated profiles matching



Lateral fluence

Measured diagonal profile is used to correct the lateral fluence initially calculated, to accurately match the shape of the linac delivered profiles



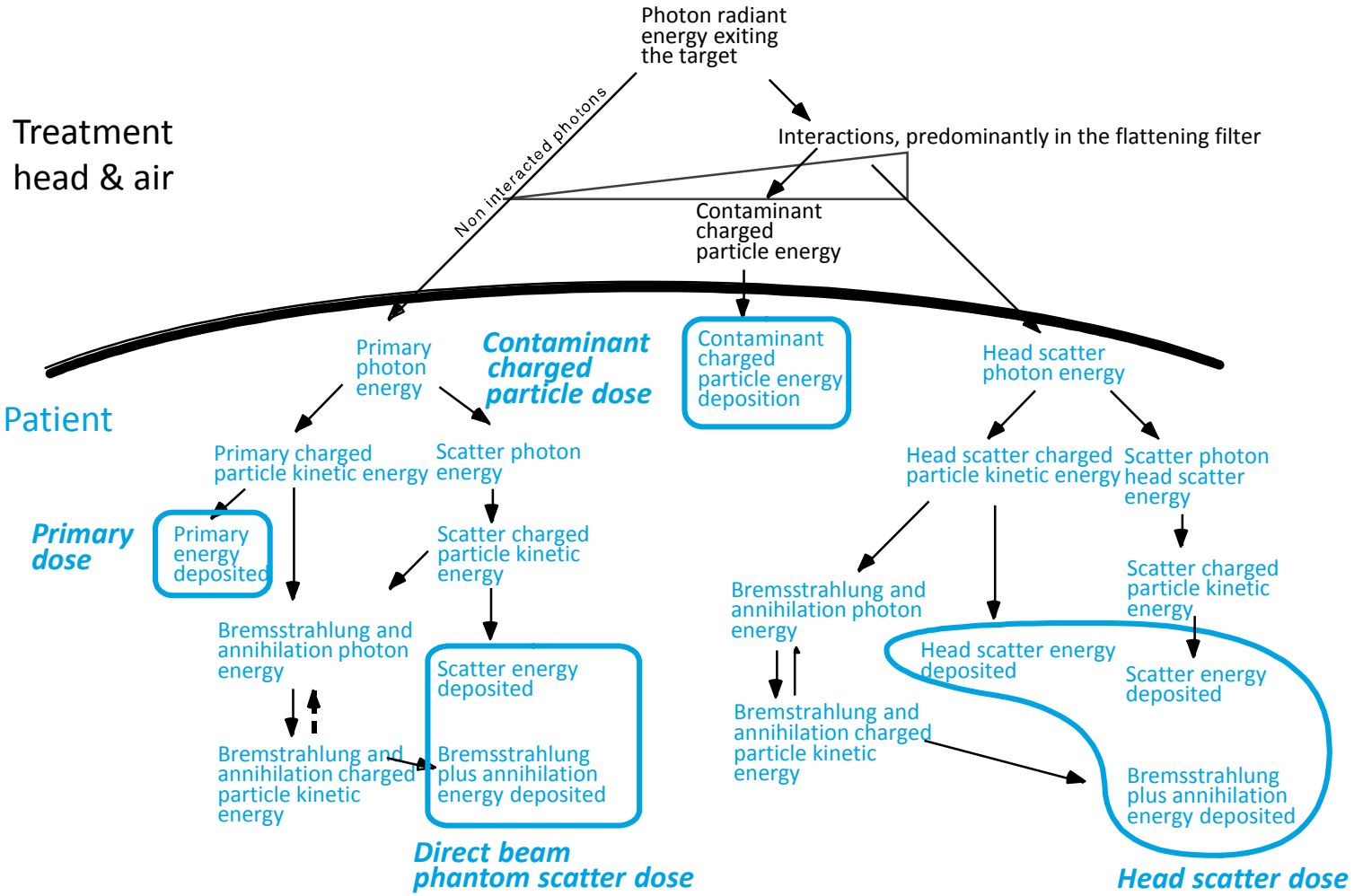
Overview of Photon Collapsed Cone algorithm

- Photon Collapsed Cone algorithm
- General description
- Fluence engine
- Dose calculation
- Usage of measured data for Collapsed Cone modeling

General description

Analytical fluence description

Superposition dose calculation



Photon Collapsed Cone algorithm

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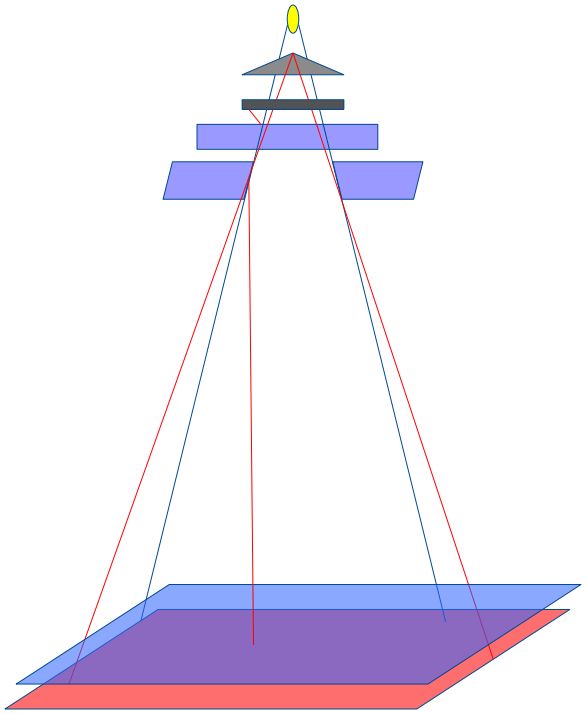
Fluence engine

Collapsed Cone is a fluence based algorithm. Direct (primary) and indirect (scatter from flattening filter, collimators, wedges…) fluence is adjusted against the measurements from the particular linac.

$$\Psi_{\text{tot}}(A;x,y)=\Psi_{\text{direct}}(x,y)\cdot\eta(x,y)+\Psi_{\text{indirect}}(A;x,y)$$



Photon Collapsed Cone algorithm

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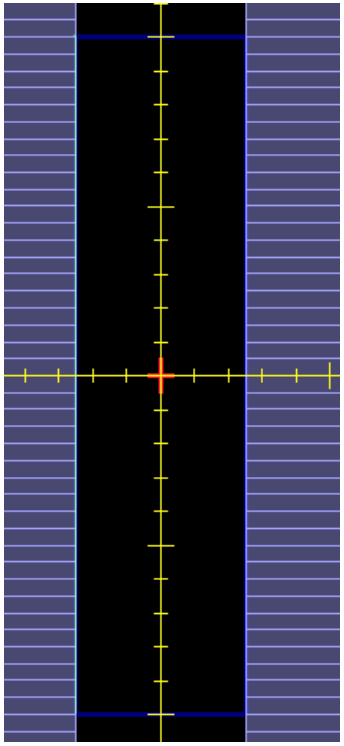
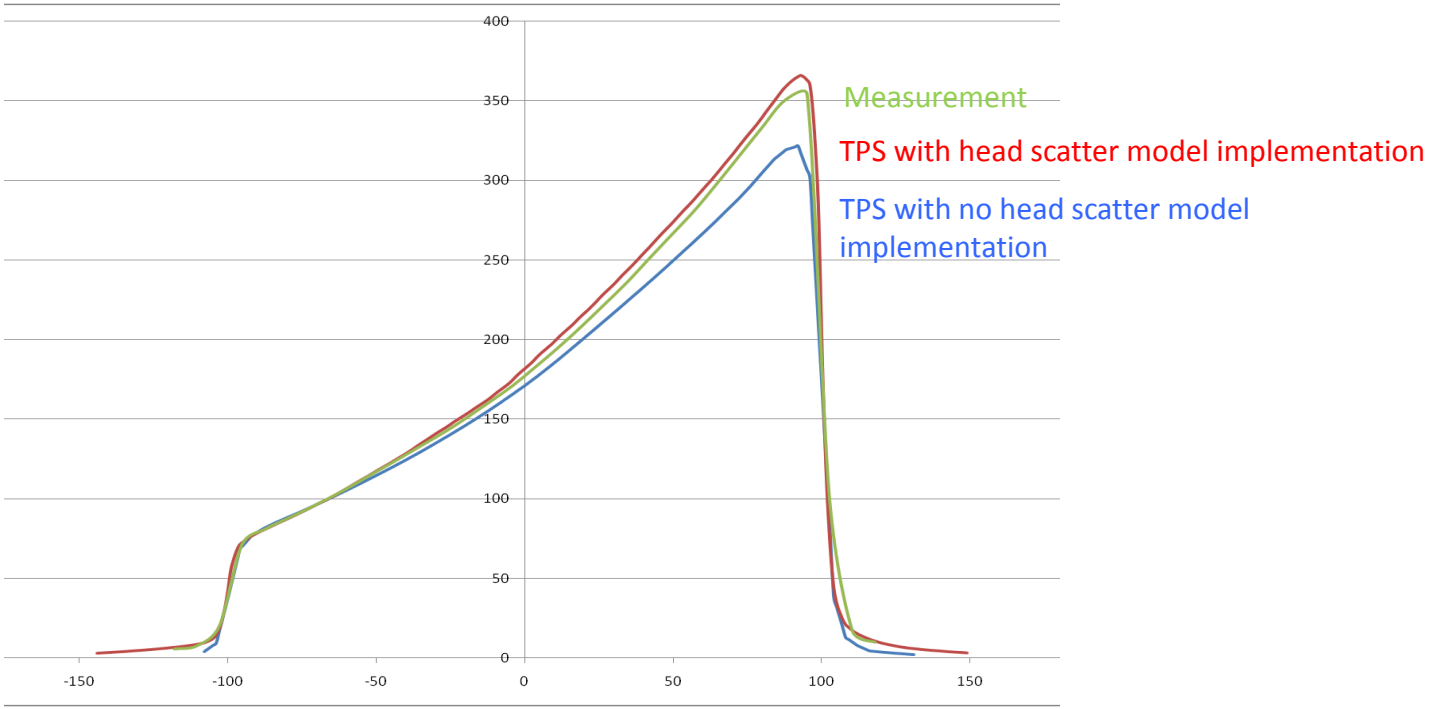
Fluence engine

Having a good model for the indirect fluence, naturally allows accurate calculations for irregular fields and beams with modifiers such as wedge:

5x20 60degree wedge





Photon Collapsed Cone algorithm

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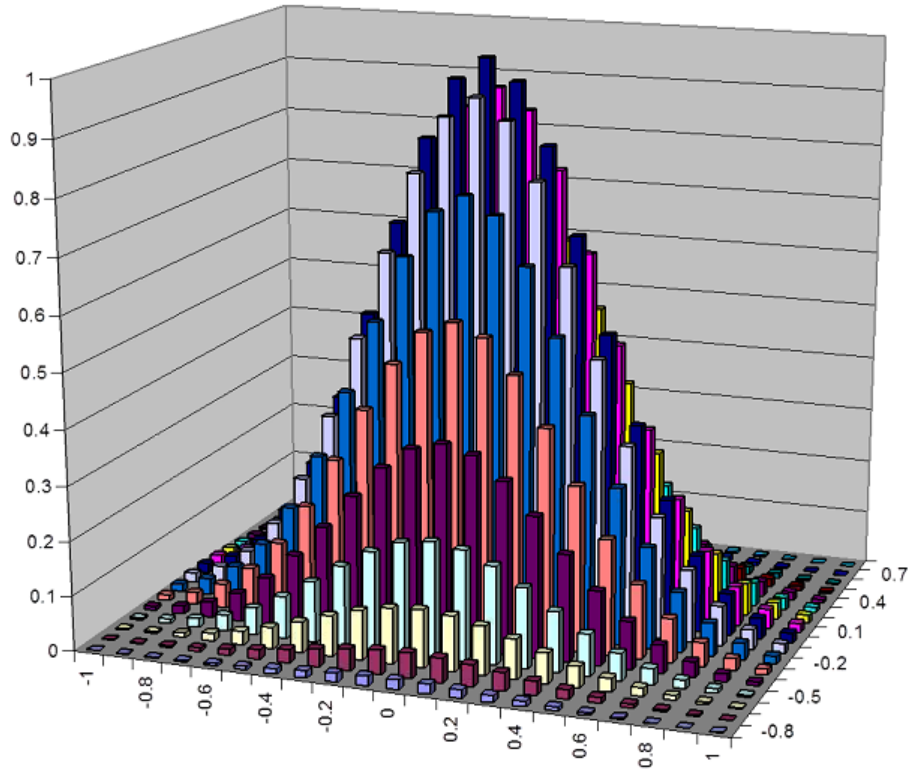
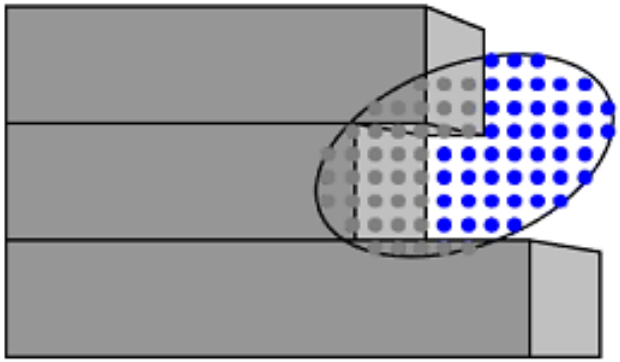
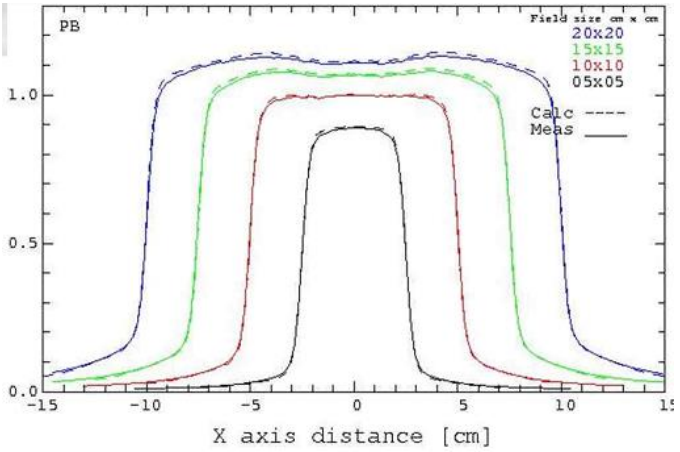
Fluence engine

Primary source is considered as an actual extended source (2D matrix), instead of a point source, improving the penumbra regions calculations.







Photon Collapsed Cone algorithm

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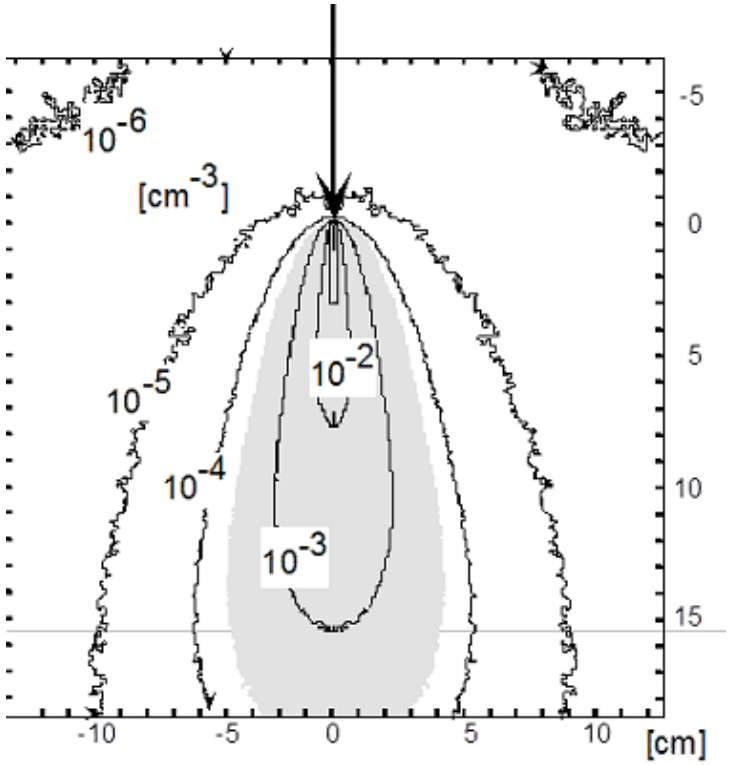
Dose calculation

Once the fluence is accurately characterized, dose calculation within the patient is done by using collapsed cone superposition algorithm, mainly based on monte carlo pre-calculated energy deposited kernels:



Photon Collapsed Cone algorithm

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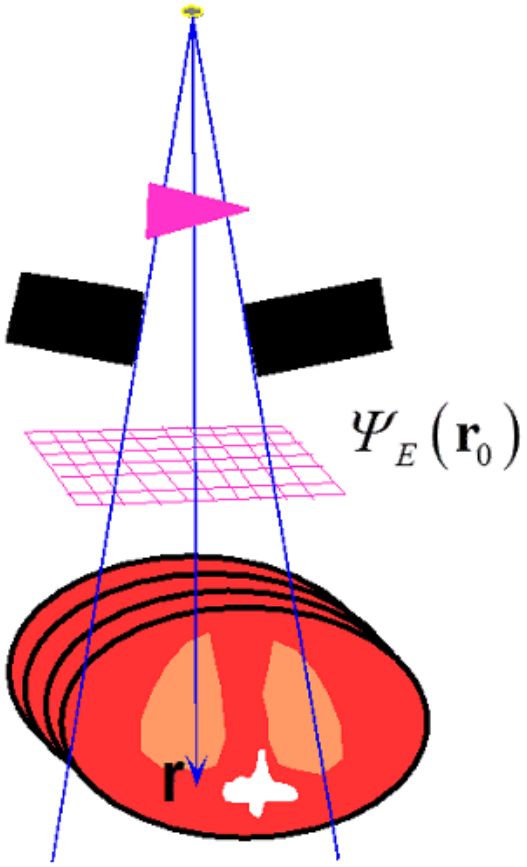
Dose calculation



- Energy released corresponding to primary dose and phantom scatter dose are calculated separately as collision kerma and scerma, respectively

TERMA (*Total Energy Released per Mass*)

$$T(\mathbf{r}) = \int_E \frac{\mu}{\rho}(E,\mathbf{r}) \quad \Psi_E(\mathbf{r})\,\mathrm{d}E$$

Collision KERMA (*the released energy to become primary dose*)

$$P(\mathbf{r}) = \int_E \frac{\mu_{\mathrm{en}}}{\rho}(E,\mathbf{r}) \quad \Psi_E(\mathbf{r})\,\mathrm{d}E$$

"SCERMA" (*the released energy to become scatter dose*)

$$S(\mathbf{r}) = \int_E \frac{\mu-\mu_{\mathrm{en}}}{\rho}(E,\mathbf{r}) \quad \Psi_E(\mathbf{r})\,\mathrm{d}E$$

- Beam hardening and off-axis softening are included in the ray trace, and modeled by mean of separate set of parameters for kerma and scerma.

Photon Collapsed Cone algorithm

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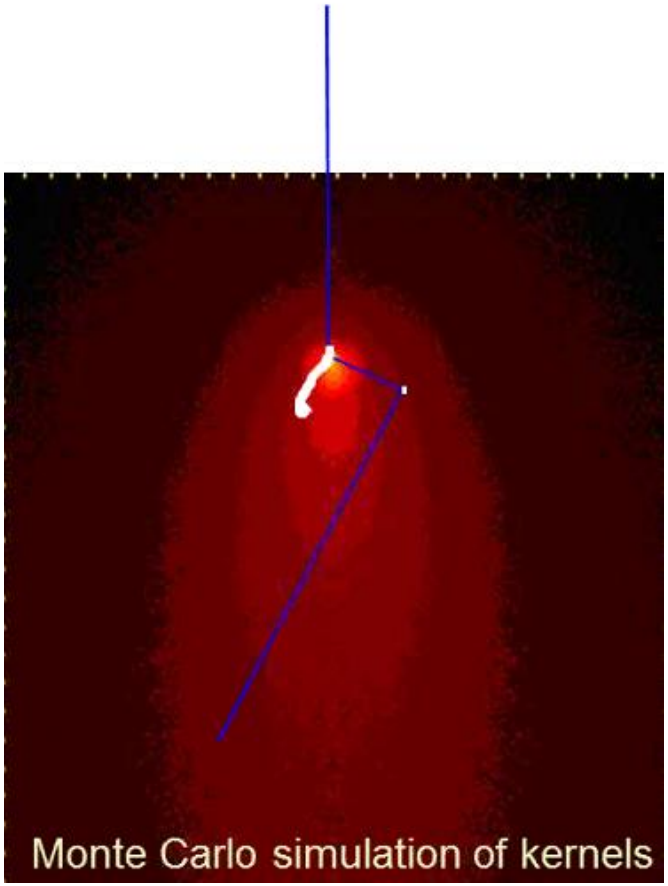
Dose calculation: kernel parametrization



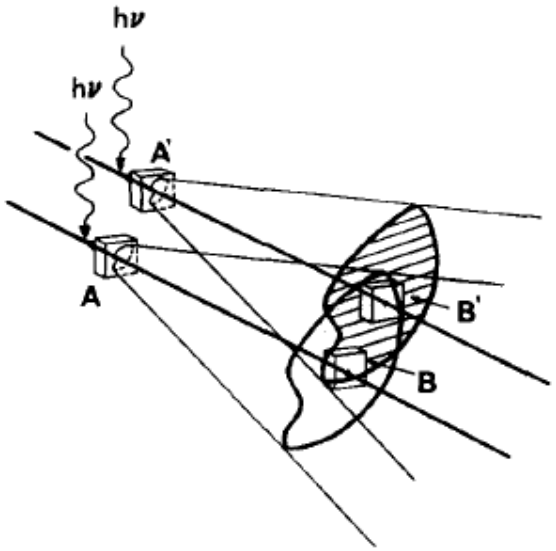
- Secondary particle transport and energy deposition are described by point kernels

- Polyenergetic kernels are parametrized:

$$h(r,\theta) = \frac{A_\theta \, \mathrm{e}^{-a_\theta r} + B_\theta \, \mathrm{e}^{-b_\theta r}}{r^2}$$

- Heterogeneities are considered scaling the kernels based on the relative electron density between interaction and deposit points.

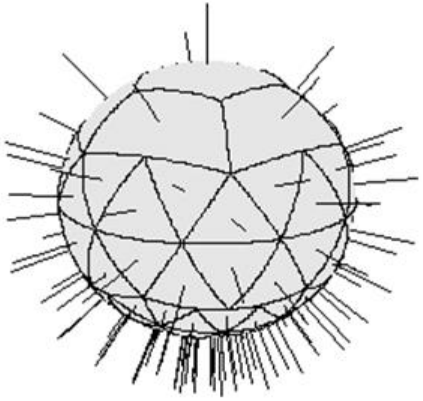
Dose calculation: transport collapsed



- The convolution is facilitated using the collapsed cone approximation

- The basic idea is that all energy emitted in a solid angle cone is assumed to be transported along the cone axis

- The kernels are discretized for a set of directions (more closely distributed in the forward direction where most of the energy of the secondary particles flow):

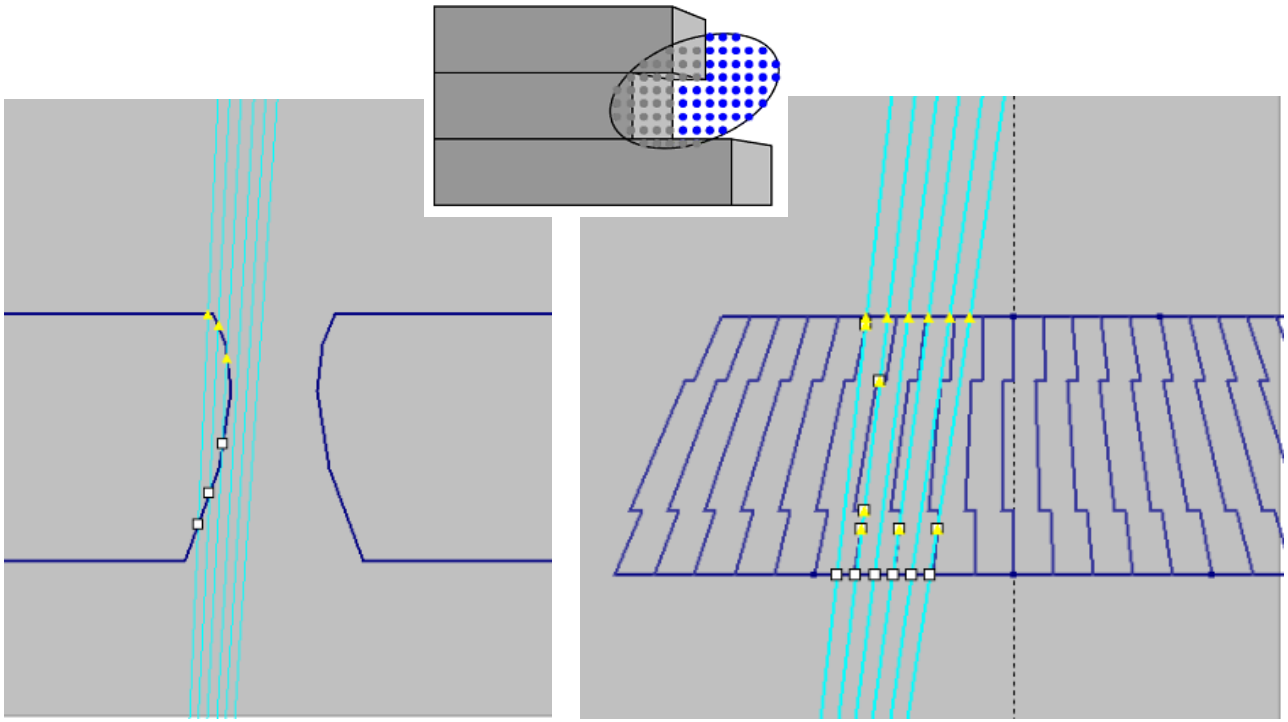


- Monaco standard configuration uses 106 different directions

Dose calculation: MLC modeling

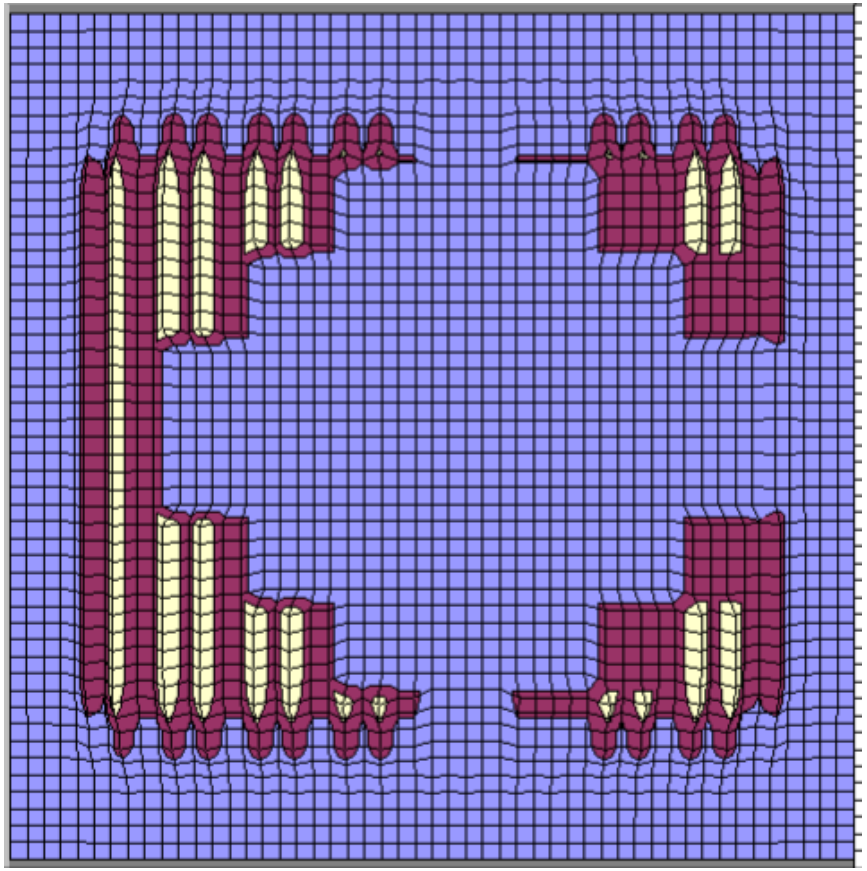
The primary fluence is modulated based on the amount of source viewed from the calculation point.

The transmission for each ray is determined based on the path length through the leaf bank:



Dose calculation: MLC modeling

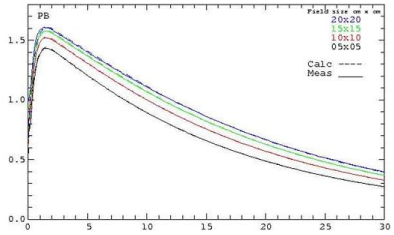
Interleaf leakage is considered in CC models. The value is set during the modeling process.



Usage of measurements for CC modeling

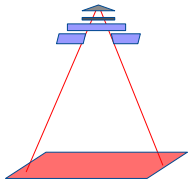
Spectrum

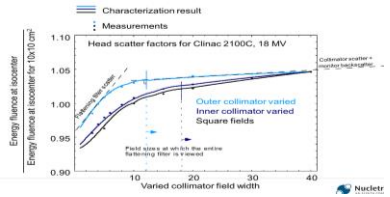
Is determined comparing calculations against measured PDDs for open fields



Indirect fluence

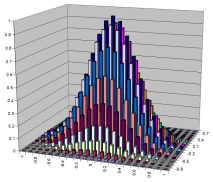
The parameters that characterize energy fluence coming out from the flattening filter, are adjusted based on the comparison of measured vs calculated in air output factors:

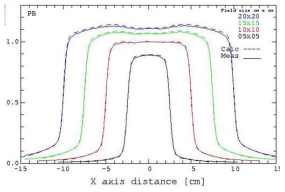




Extended primary source

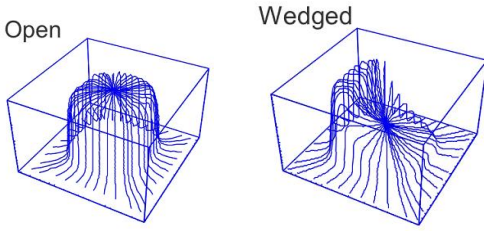
The dimensions of the source are adjusted comparing measured vs calculated profiles at the penumbra region





Lateral fluence and fluence modulation

To model the lateral direct lateral fluence, measured diagonal profiles are used to compared the calculations, and adjust it in an iterative process, until calculation and measurement match. Measured diagonal profiles with wedge are used to derive a wedge modulation matrix, which will be used to modify the fluence for open beam.

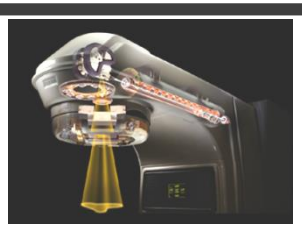


Overview of Electron Monte Carlo algorithm

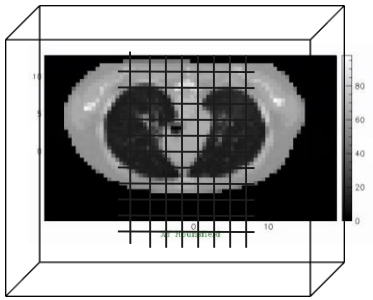
- Electron Monte Carlo algorithm
- General description
- Source and Exit phase space
- Dose calculation
- Usage of measured data for Collapsed Cone modeling

General description

The purpose of the MC beam model is to create a stream of particles representative of the radiation field from the real linac!



Coupled Multi-Source phase space engine



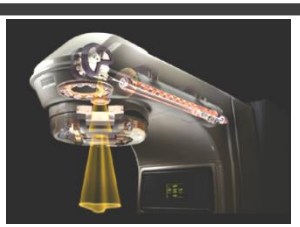
In patient dose calculation by VMC++

General description

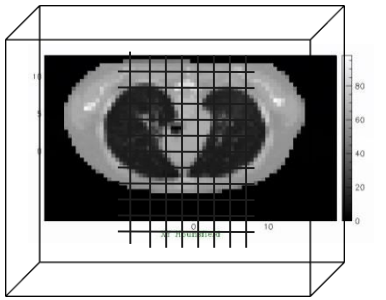
Two independent components:

Electron phase space engine:
- A ”Coupled Multi-Source” beam model
- Developed in house (Uppsala, Sweden)
- Full control of beam characterization
- Characterization by STUNT+TUC

MC dose engine:
- VMC++ code by Iwan Kawrakow
- Current state-of-the-art MC code
- Both for electrons and photons
- Licenced from NRC (National Research Council),Ottawa, Canada



Coupled Multi-Source phase space engine

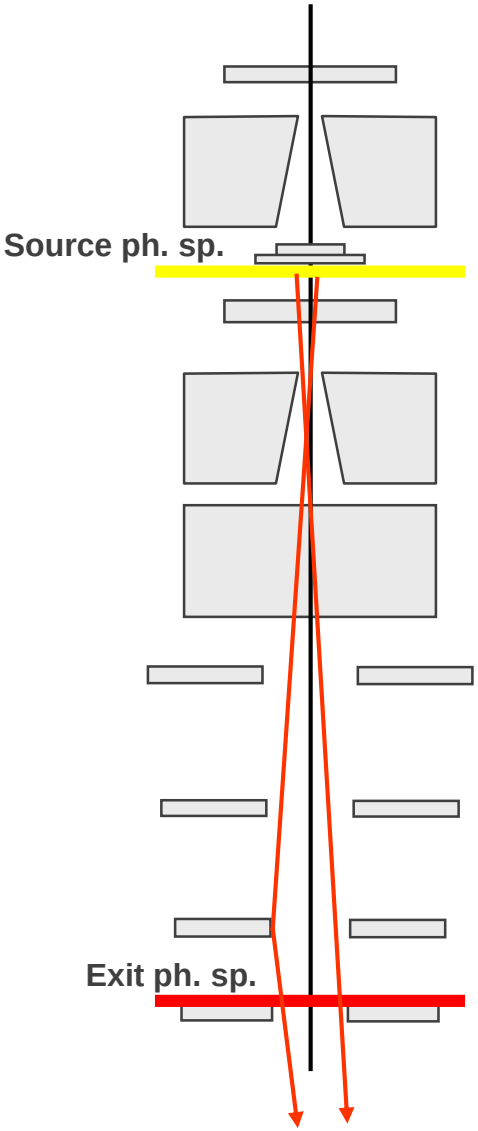


In patient dose calculation by VMC++

Source and Exit phase spaces

Source phase space:
Electron beam is parameterized by energy spectrum and five spatial-angular parameters in a plane close to the secondary scattering foil.

Exit phase space:
Source phase space is propagated to and parameterized in a plane before the first variable collimator.



Source and Exit phase spaces

Fluence components:

Direct fluence:

Electrons that have not interacted with any collimating elements.

Indirect fluence:

i. Electrons emitted from collimating elements due to irradiation by the direct fluence.

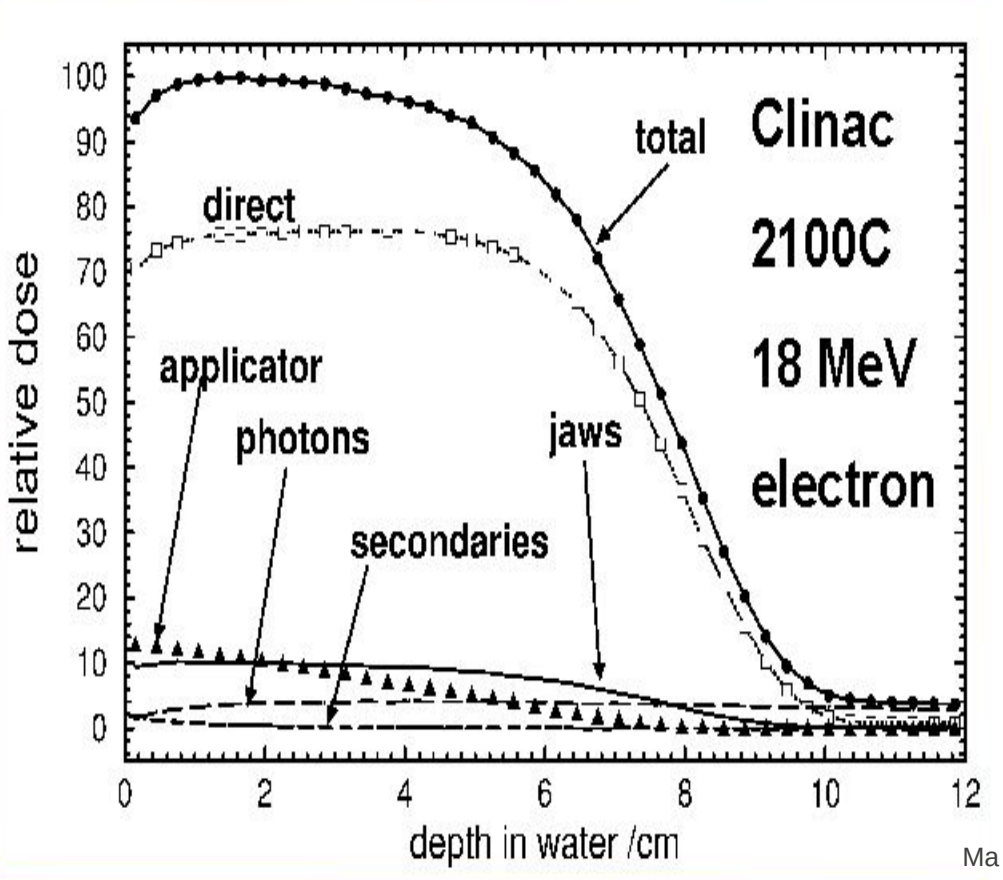
ii. Treatment head generated bremsstrahlung photons.

At run-time indirect electrons are sampled from *pre-calculated* scatter kernels. The scatter source is coupled to the source phase space via the direct electron fluence incident onto the collimator rims.

Source and Exit phase spaces

Fluence components:

As an example:



Scattered particles 10-20% of beam !

Ma et. al, Med. Phys **24**, 401-416(1997)

Electron Monte Carlo algorithm

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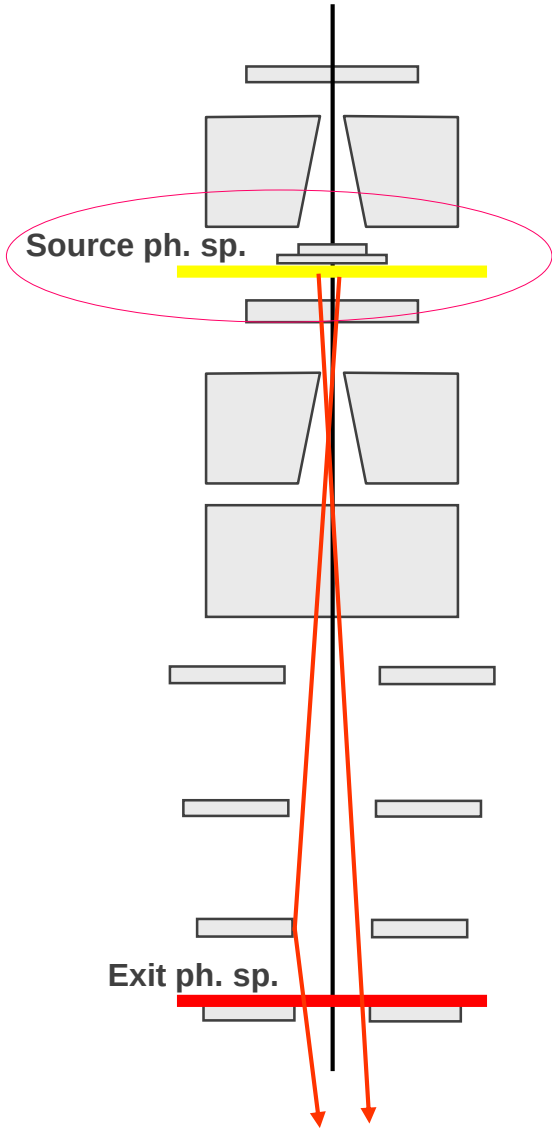
Source and Exit phase spaces

Source phase space:

Note 1: Spectrum of direct electrons common to all applicators.

Note 2: The difference between open and non-open fields are due to indirect electrons and for small fields also loss of lateral charge equilibrium.

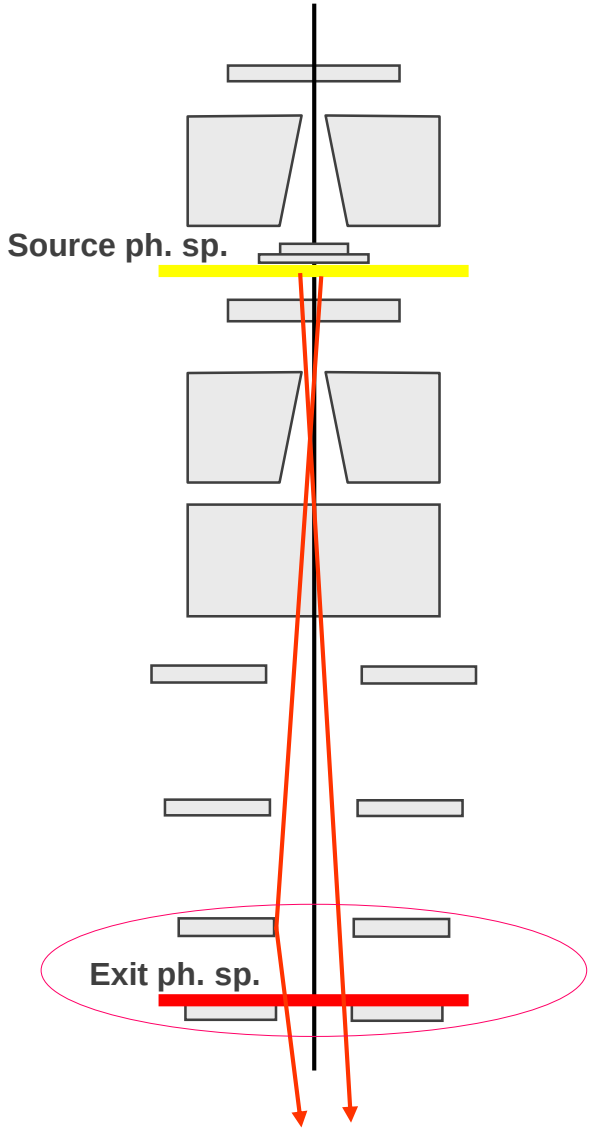
Note 3: It is assumed that the spectrum is independent of lateral position (x,y). Use same spectrum over whole applicator exit.



Source and Exit phase spaces

Exit phase space:

Found by propagating source phase space to the exit phase space plane using a dedicated MC code (QMC).

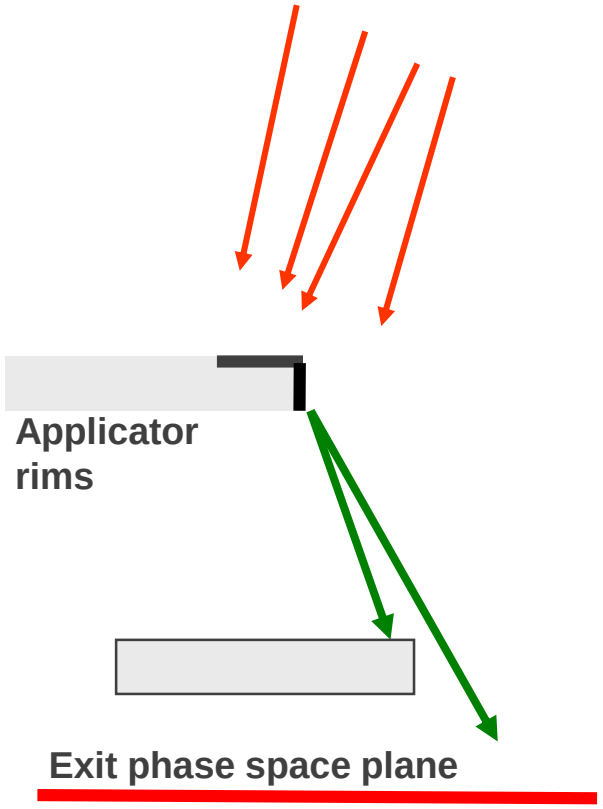


Source and Exit phase spaces

Exit phase space:

While propagating source phase space score fluence incident on aperture rims.

At run-time dose calculation this *pre-calculated* result is used for sampling indirect electrons from *pre-calculated* scatter kernels and transporting them to the exit phase space plane.



Source and Exit phase spaces

Bremsstrahlung:

Dose distribution from photons is modeled through an empirical energy dependent depth dose from the linac head bremsstrahlung, combined with a gaussian shape in the lateral dimension.

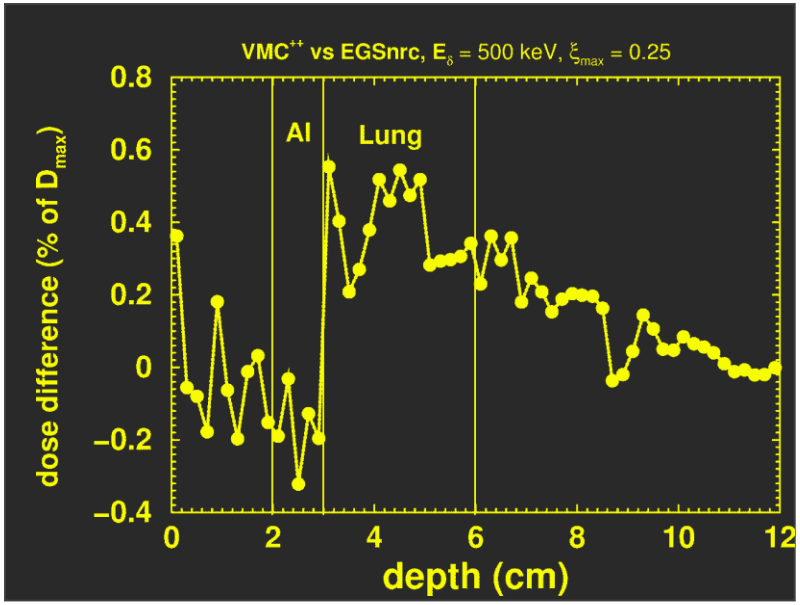
The width of the lateral gaussian is obtained by fitting against measured profiles at a depth beyond the electron range..

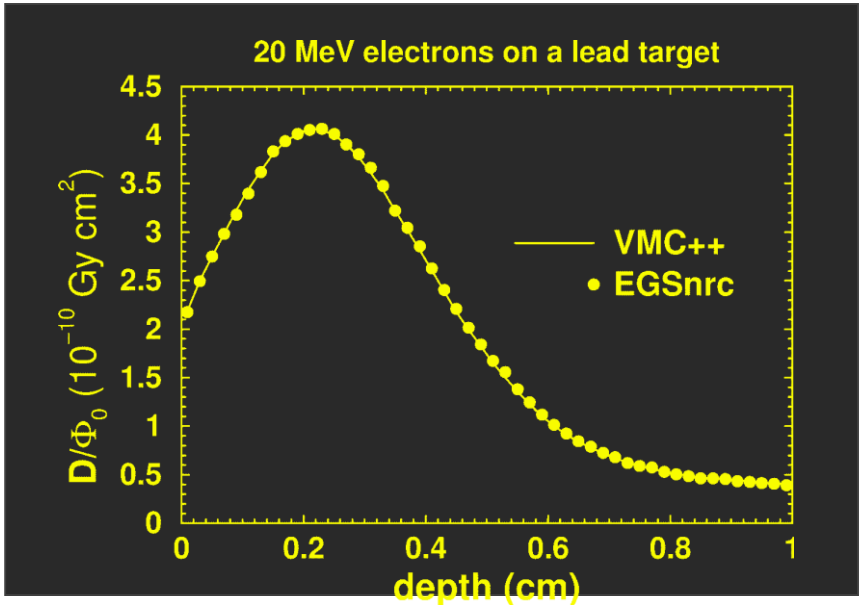
Dose calculation

VMC++

Exit phase space is used to run Monte Carlo calculation by using VMC++ algorithm within the phantom.

VMC++ is a validated accurate algorithm:

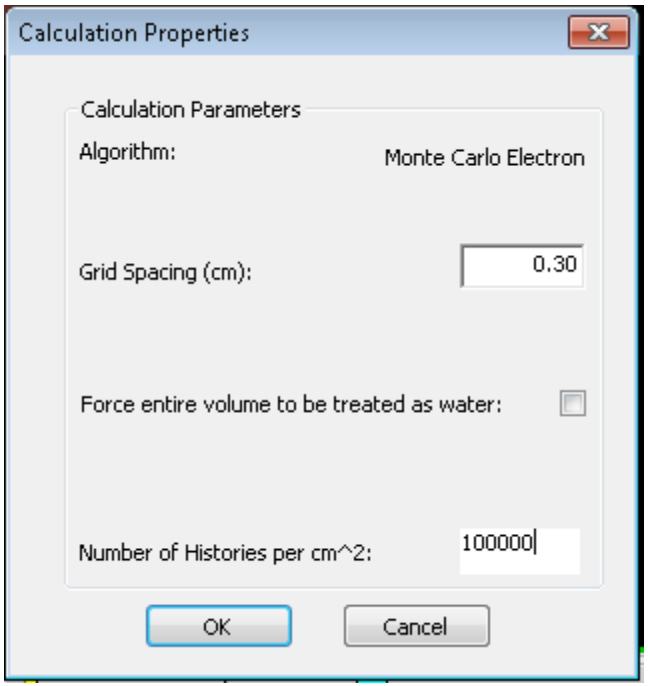




Dose calculation

VMC++

In Monaco, the uncertainty of the calculation is defined through histories/cm^2.
A reasonable value to use is about 100.000 histories/cm^2. For QA purposes, this can be raised up to about 106 histories/cm^2. The seed is fixed, so that the calculation will be the same all the time.



Usage of measurements for eMC modeling

Spectrum

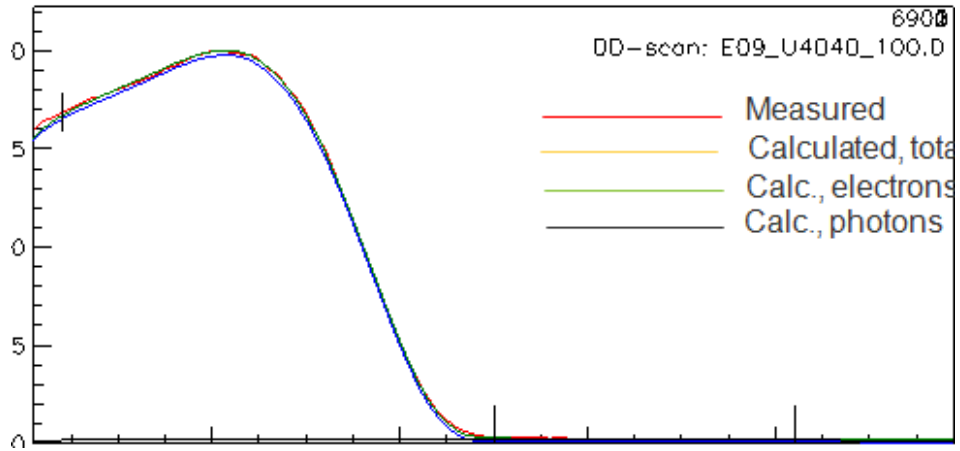
Energy spectrum is based on a measured open field (without applicator) depth dose (DD) in water.

Energy spectrum is specified by an analytical function with parameters whose values are found by fitting a calculated DD towards a measured DD.

No applicators, so no indirect electrons. Enough to consider direct electrons and Bremsstrahlung.

Calculated DD is weighted sum of monoenergetic depth doses (calculated by VMC++) with weights defined by the spectrum function.

Surface region excluded in the depth dose fit.

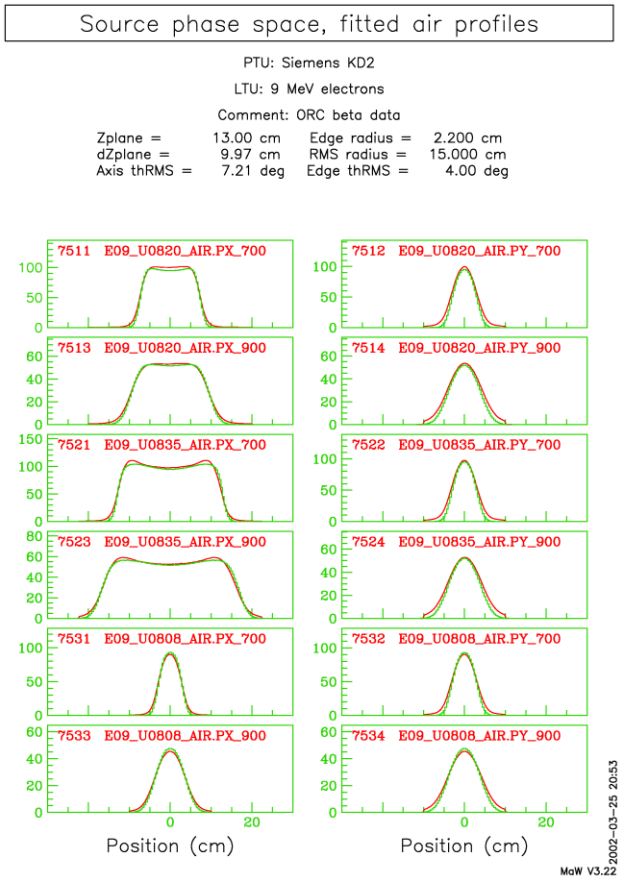


Usage of measurements for eMC modeling

Spatial – Angular parameters of source

Source phase space parameters such as distance from virtual source to phase space plane, source width…, are found by optimizing simulated in-air fluence profiles.

Simulation uses dedicated MC code (QMC) for the transport from source phase space to exit phase space.



Algorithms

- For pMC, the history density is directly defined by the user. True or False?
- When a pMC plan is calculated two times, it will be common to find dose differences of about 2 times the statistical uncertainty. True or False?
- In Monaco Collapsed Cone, as the scatter from the primary collimator and flattening filter as the scatter from the wedge is accounted for in the calculation. True or False?
- If a user don't have the instrumentation required to measure the in air OF for Collapsed Cone data, the model can still be created with the rest of the measured data. True or False?
- eMC measurements without applicator are very important because…

QUIZ time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