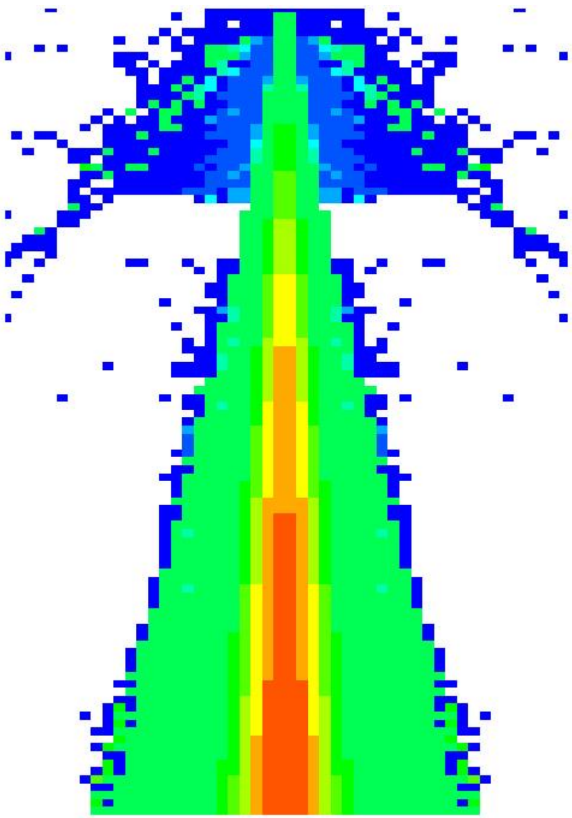
Ant colony algorithm for driving variance reduction techniques in Monte Carlo simulations



Salvador García-Pareja

Gloria Díaz-Londoño

Fabián Erazo

Francesc Salvat

Antonio M. Lallena

JUNTA DE ANDALUCIA

Servicio Andaluz de Salud
CONSEJERÍA DE SALUD

UNIVERSIDAD DE LA FRONTERA
TEMUCO · CHILE

SOLCA

UNIVERSITAT DE BARCELONA

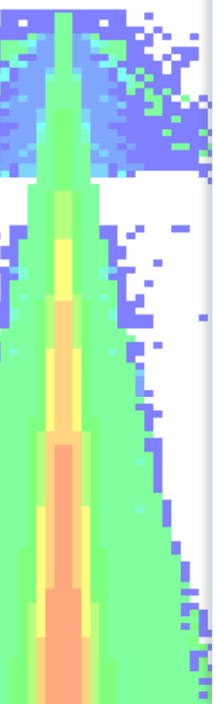
Universidad de Granada

Introduction

The Monte Carlo simulation is a useful tool in the study of radiation transport.

High degree of agreement with experimental measurements.

↑ Precision → ↑ Simulation time



Variance reduction techniques can solve the problem.

Introduction

Variance reduction techniques:

- Russian Roulette, splitting, interaction forcing, etc.
- Statistical weight is assigned to every particle for keeping the simulation unbiased.
- Used properly they can increase efficiency. Otherwise, efficiency could even decrease.

How to use them properly?

Aim of this work: To find an algorithm that permits the application of these techniques optimizing the simulation with a minimal intervention from the user.

The algorithm has been developed studying different situations regarding medical applications of ionizing radiation.

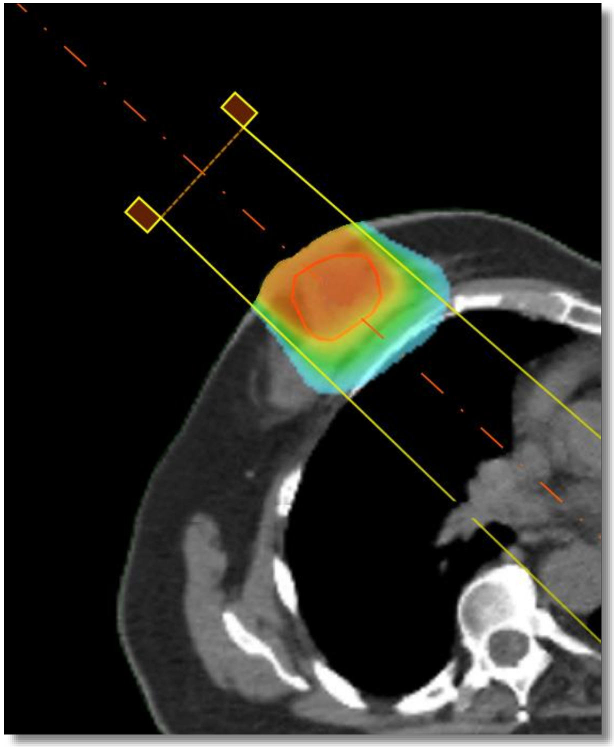
We have chosen the PENELOPE Monte Carlo code for the radiation transport simulations.

Electron beams

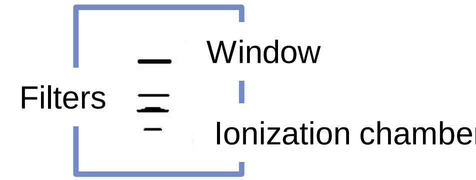
Widely used in near-surface treatments.

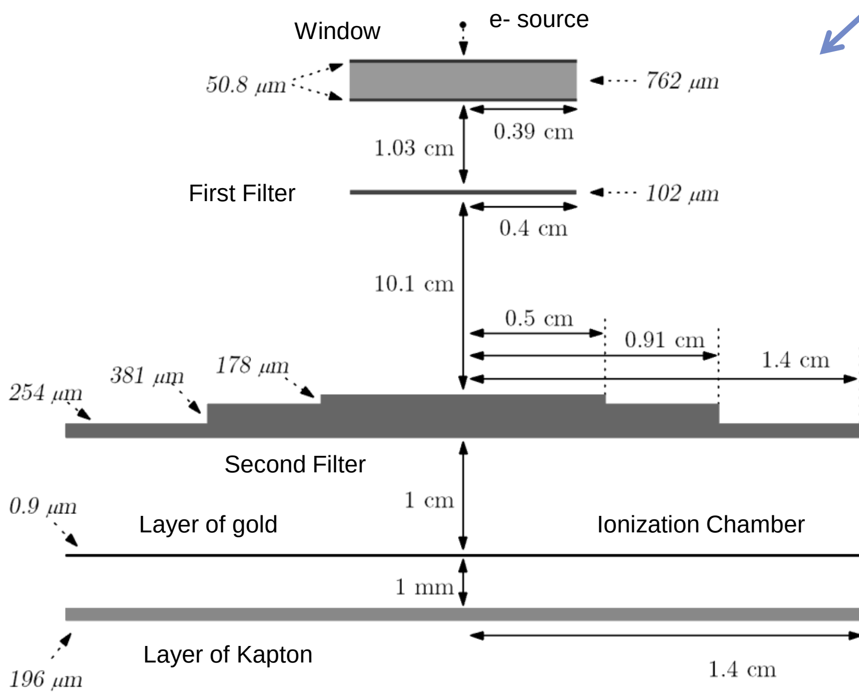
In the presence of heterogeneities MC is the best choice of calculation.

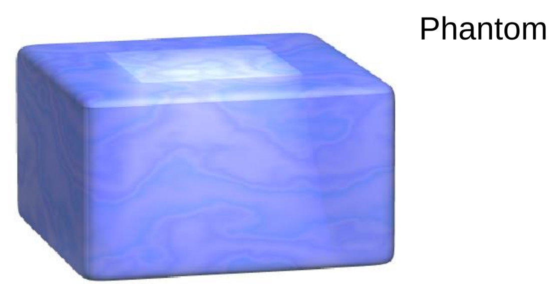
Essential a good characterization of the beam.

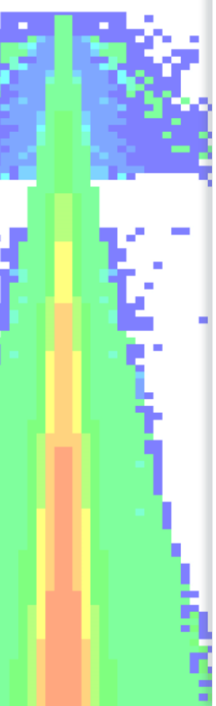


Geometry of Mevatron Siemens KDS accelerator

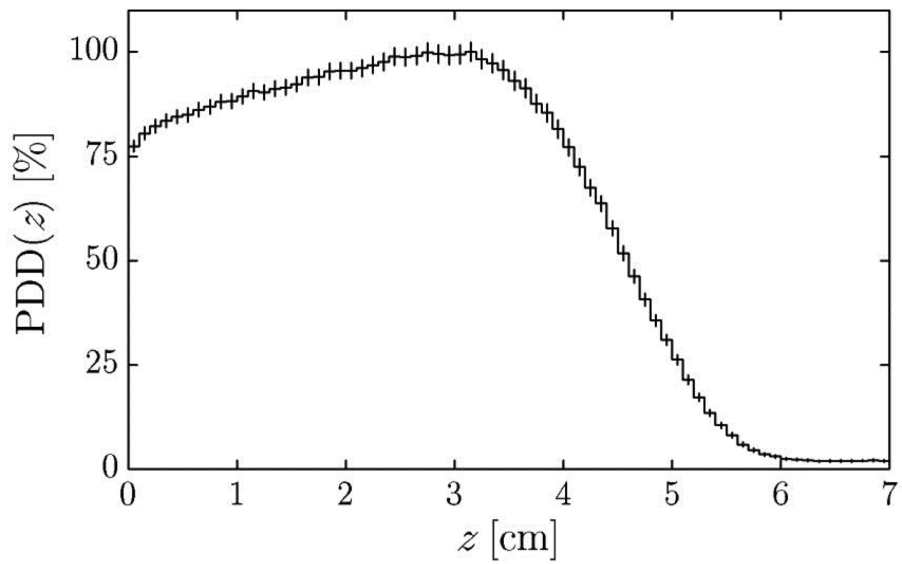






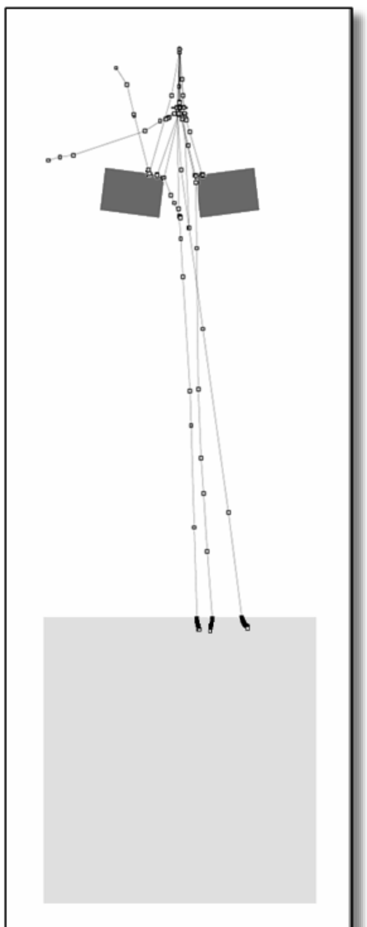


12 MeV electron beam PDD in a water phantom.



Typical simulation parameters. PC Pentium 4 (1.6 GHz).
Time to reach 2% uncertainty ($k = 3$): 220 h.

The problem

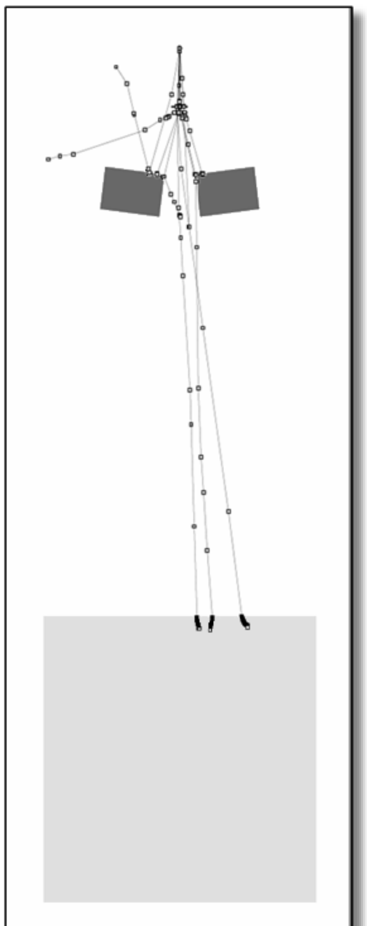


Most of that time is spent simulating electrons that are absorbed by the jaws (~ 80%).

Possible solutions for electrons:

- Russian Roulette: Reduce time but increases variance.
- Splitting: Reduce variance but increases simulation time.

- The problem



Where to apply Russian roulette or splitting?

Test simulations

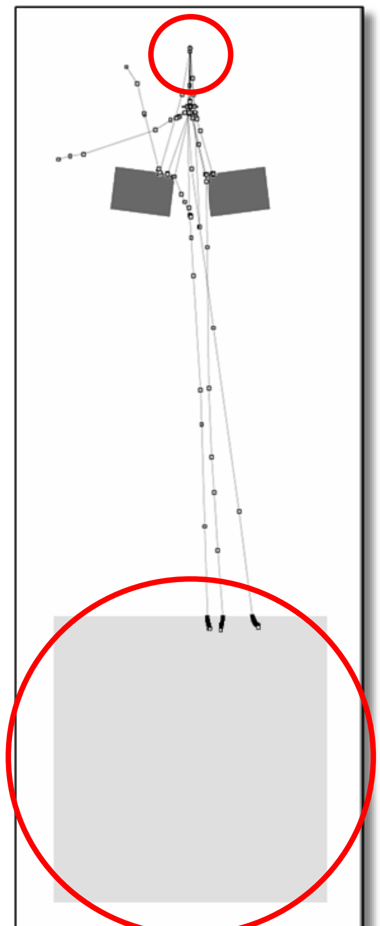
Optimization algorithms

Ant Colony Optimization Algorithms

Algorithms based on ant behavior:

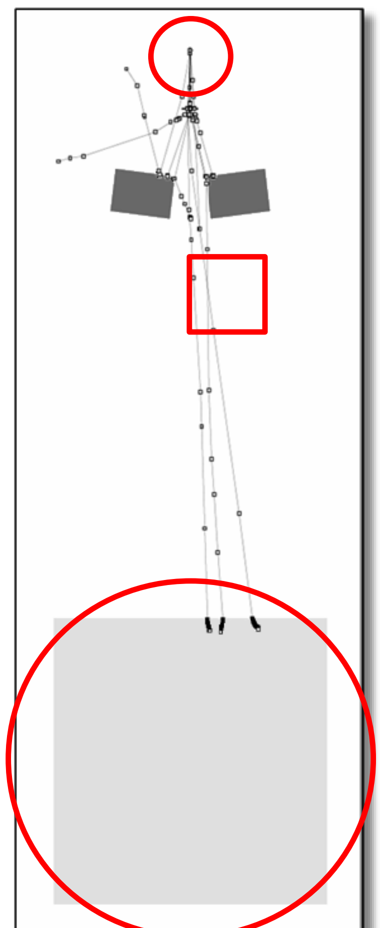
- Ants look for food following a random walk.
- If they find food, then they come back to the nest depositing pheromone.
- The other ants tend to follow the pheromone trail.
- The overall effect is an increased deposition of pheromone on the optimal path between food and nest.

- Analogies with our problem:



Nest	➞	Particle Source
Food	➞	Water phantom
Pheromone	➞	Importance

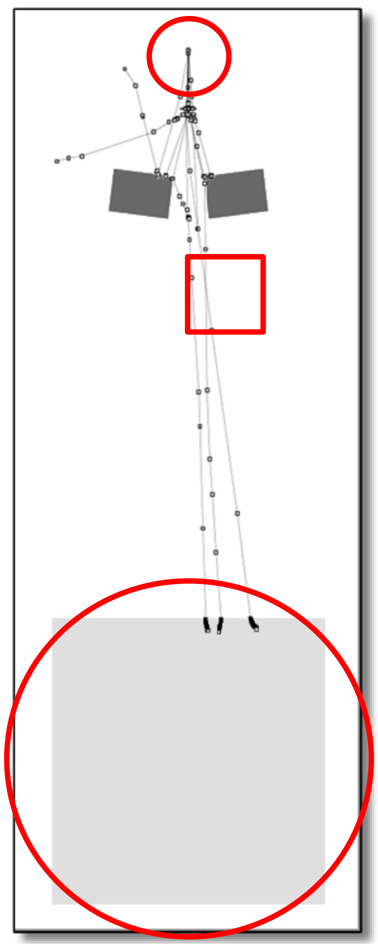
Implementation of the algorithm in simulations



First step:

- The entire geometry is divided into virtual cells.
- The simulation starts with no use of VRTs.
- The ratio of particles that passing through every cell, reach the ROI is registered during the simulation.
- Importance I in each cell is defined as a function of that ratio (Importance map).

Implementation of the algorithm in simulations

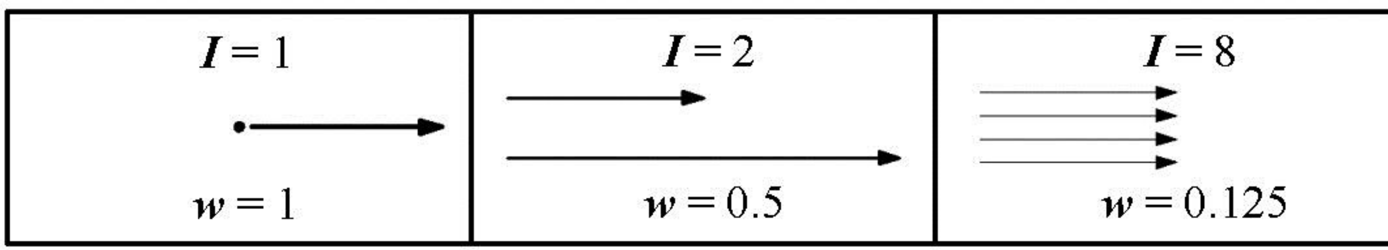


Second step:

- Once the importance map has enough information, VRTs can be used.
- Each time a particle arrives to a new cell, VRTs are applied according to the particle weight w and the cell's importance I.

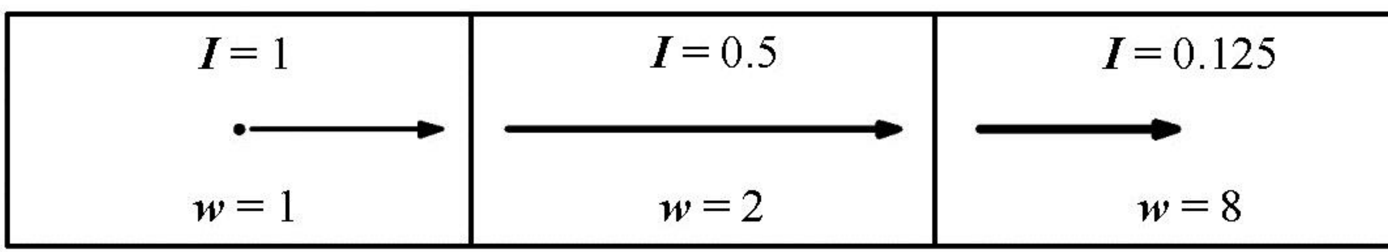
Implementation of the algorithm in simulations

- If I increases $\longrightarrow$ *Splitting* in $w \cdot I$ particles with $w' = I^{-1}$.



Implementation of the algorithm in simulations

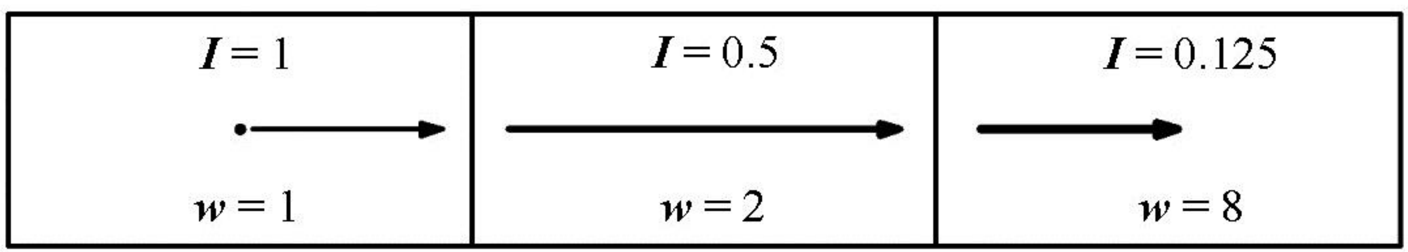
- If I increases ⟶ *Splitting* in $w \cdot I$ particles with $w' = I^{-1}$.
- If I decreases ⟶ Russian roulette with probability of survival $w \cdot I$. If it survives, $w' = I^{-1}$.



Electron beams

Implementation of the algorithm in simulations

- If I increases $\longrightarrow$ *Splitting* in $w \cdot I$ particles with $w' = I^{-1}$.
- If I decreases $\longrightarrow$ Russian roulette with probability of survival $w \cdot I$. If it survives, $w' = I^{-1}$.



- Defining $I = 2^k$, with k as integer, all particles in the same cell have the same weight.

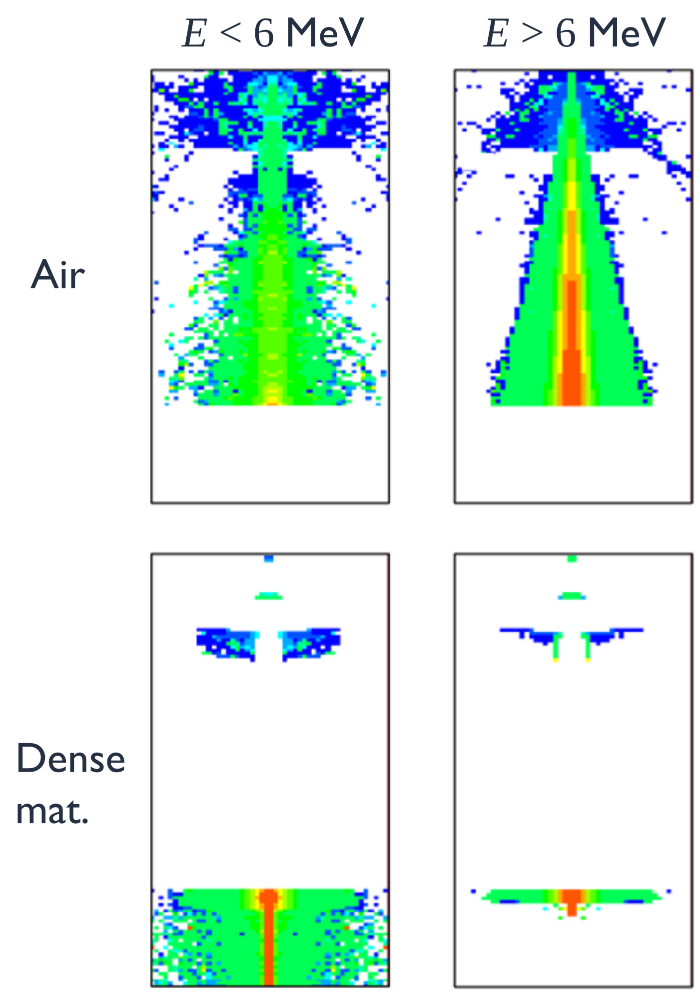
Importance map

$$I = I(x, y, z, E, m)$$

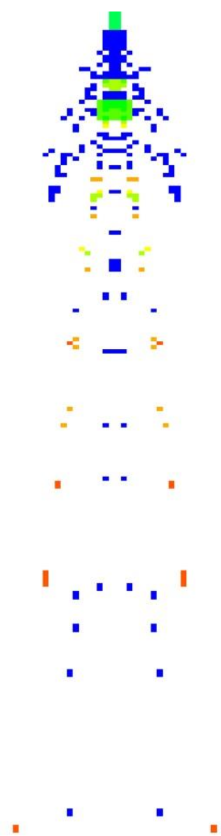
Virtual cubic cells of side 1 cm.

Two values for energy.

Two values for the material.



Importance map

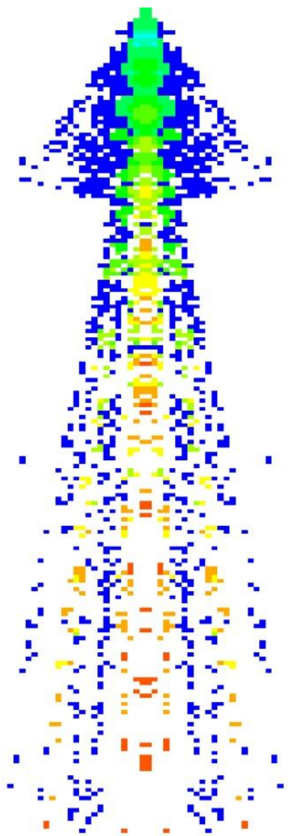


When there is few information on the map, the usefulness of the algorithm is reduced.

$$I = I(x=1, y, z, E=1, m=1)$$

$$N = 100$$

Importance map

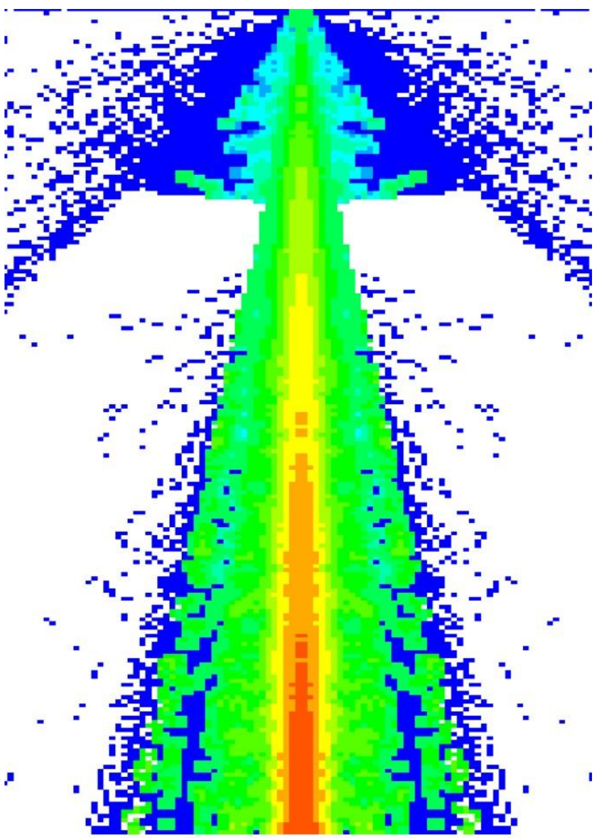


When there is few information on the map, the usefulness of the algorithm is reduced.

$$I = I(x=1, y, z, E=1, m=1)$$

$$N = 1,000$$

Importance map



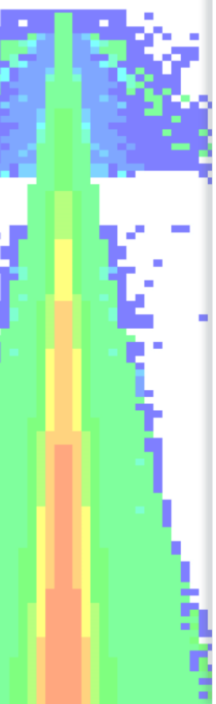
When there is few information on the map, the usefulness of the algorithm is reduced.

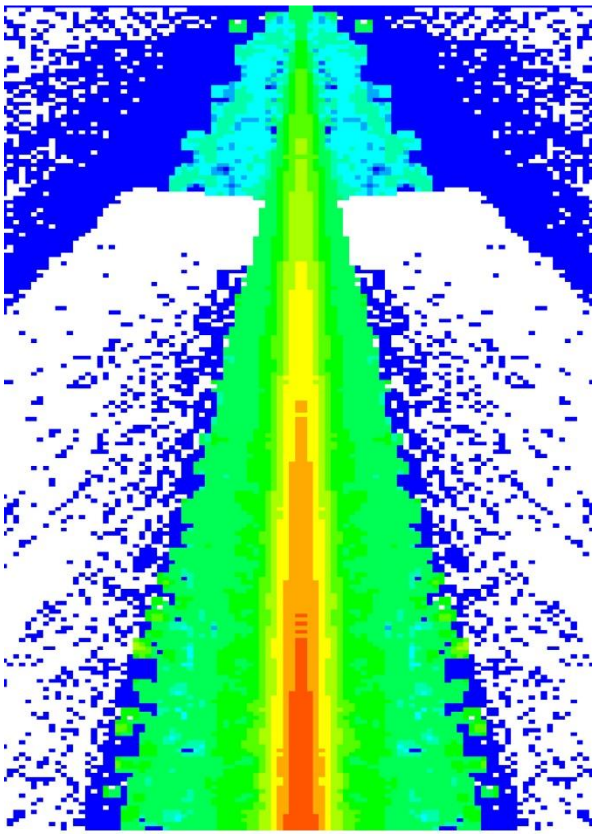
$$I = I(x=1, y, z, E=1, m=1)$$

$$N = 10,000$$

Electron beams

Importance map



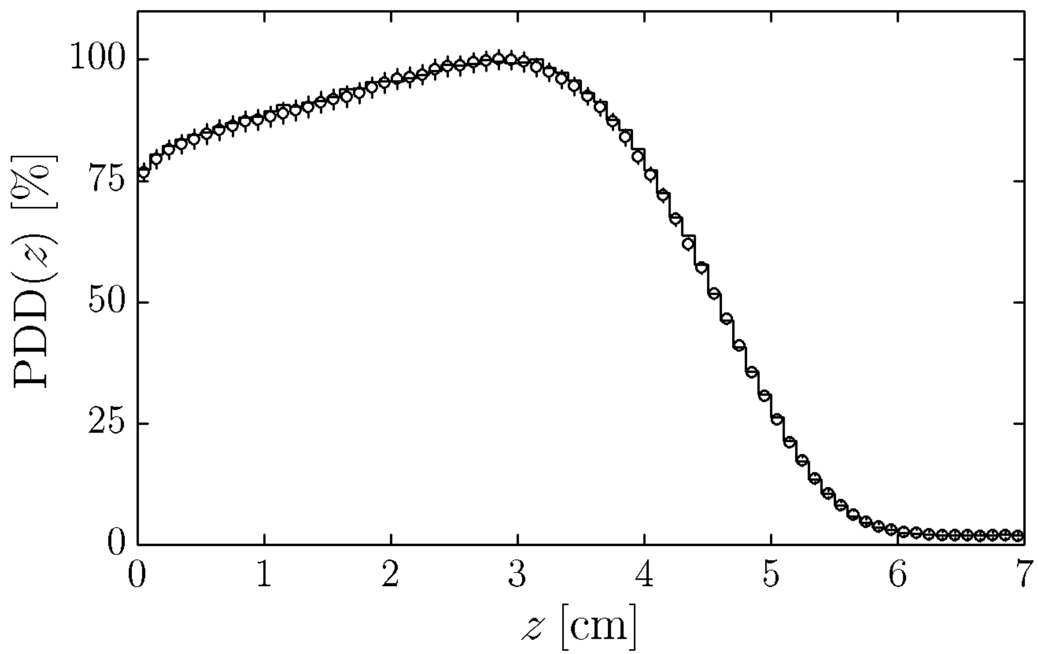


When there is few information on the map, the usefulness of the algorithm is reduced.

$$I = I(x = 1, y, z, E = 1, m = 1)$$

$$N = 500,000$$

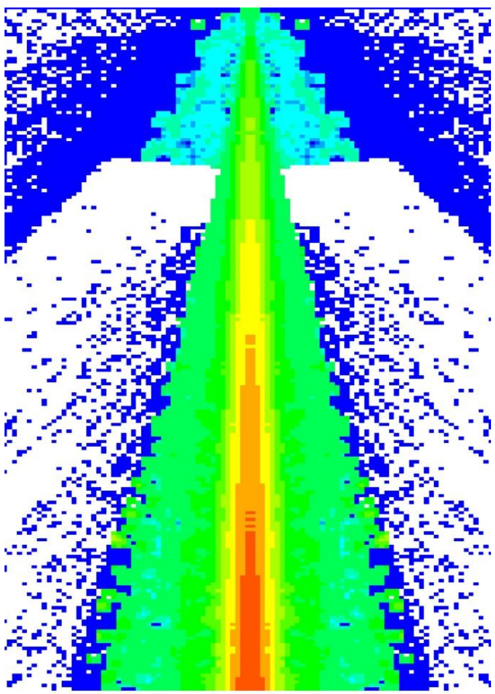
Results applying the optimization algorithm



Time simulation is reduced from 220 h to 4.4 h.

Efficiency x 50.

Electron beams

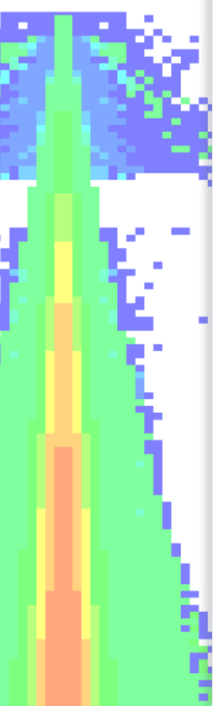


The optimization algorithm allows the efficient and automatic use of variance reduction techniques.

Tested on a particular problem.

But is this algorithm general enough?

Photon beams for radiosurgery



They are very narrow beams used for treatment of small lesions near healthy structures that has to be preserved.

The characterization of these beams is very complex due to their small size.

Monte Carlo simulations can be used as a complementary tool to experimental measurements.

Again, the simulation time can be huge.

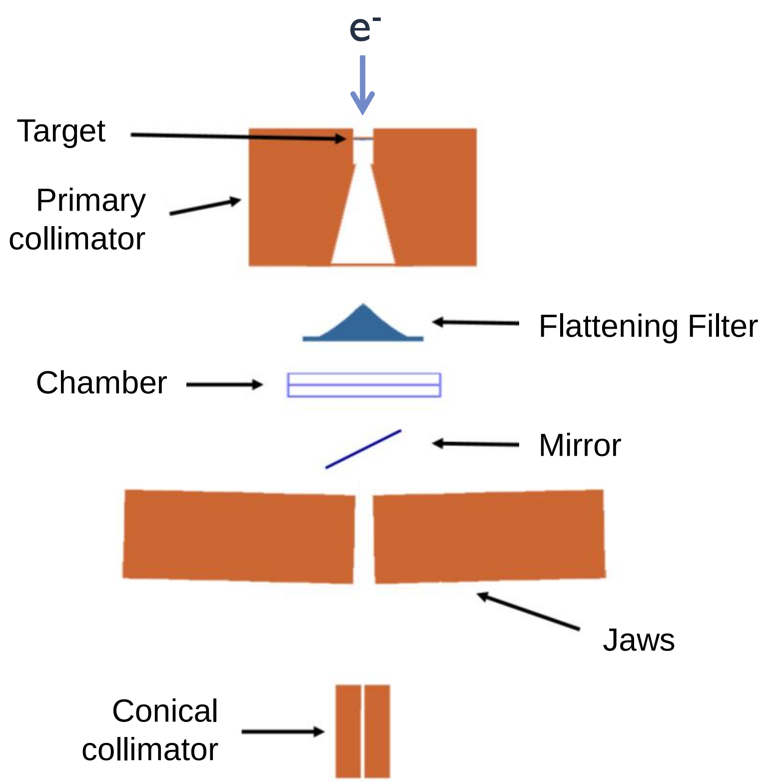
Characterization of the beams

Circular fields generated by a Varian accelerator 2100C with conical collimators.

Characterization for the treatment planner:

- Depth dose distributions and lateral profiles in water phantom.
- Output factors for each cone.

Characterization of the beams



- Tuning of the electron beam incident on a target for reproducing experimental measurements.
- We need to apply the optimization algorithm to both electrons and photons.

Application of the optimization algorithm

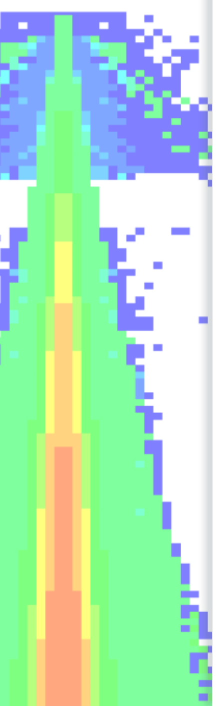
Importance maps:

$I_1 = I(x, y, z, E, M)$ for electrons.

$I_2 = I(x, y, z, E, M, \theta, \phi)$ for photons.

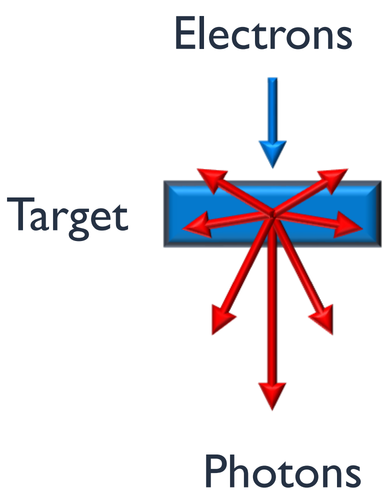
Using new variance reduction techniques with photons:

- Russian roulette and splitting $\longrightarrow$ No gain in efficiency.
- Directional bremsstrahlung splitting.



Photon beams for radiosurgery

Directional bremsstrahlung splitting

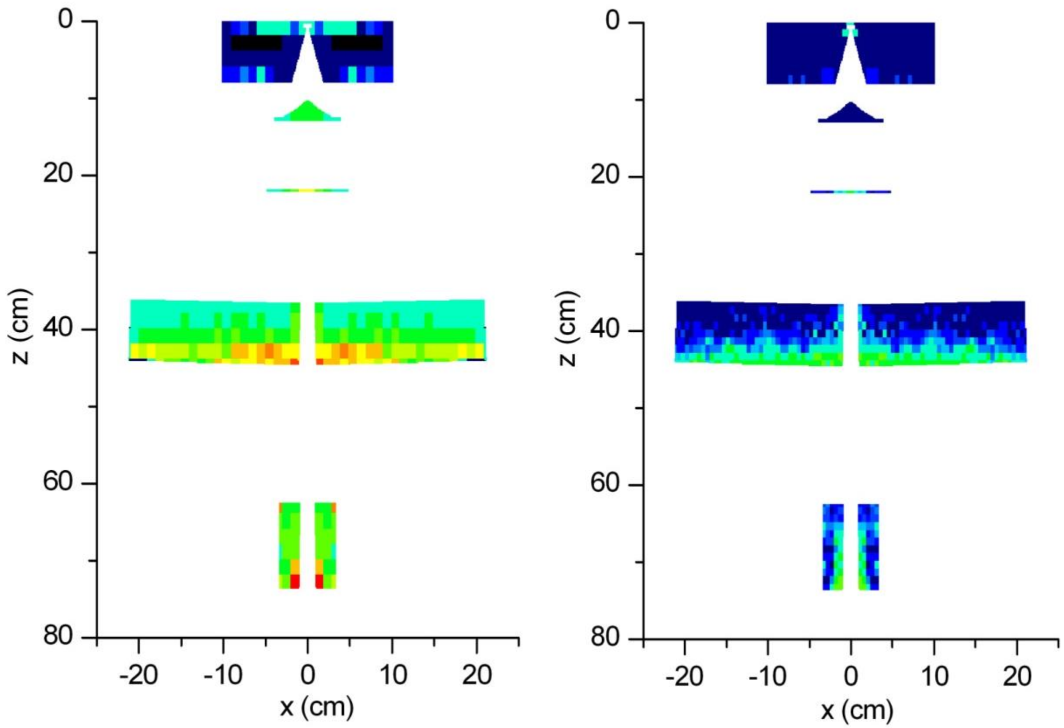


Whenever an event that produces photons occurs, the event is repeated $w \cdot N_{\mathrm{Br}}$ times.

Russian roulette is applied on each generated photon according to $w' \cdot I$.

It is used throughout the geometry and when photons are scattered.

Photon beams for radiosurgery



Left: map for high energy photons pointed to the phantom. Right: High energy electrons. Brighter colors correspond to higher importance.

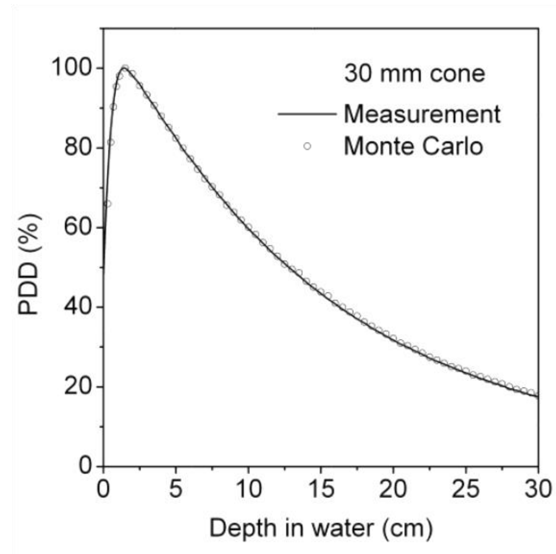
Simulation Time

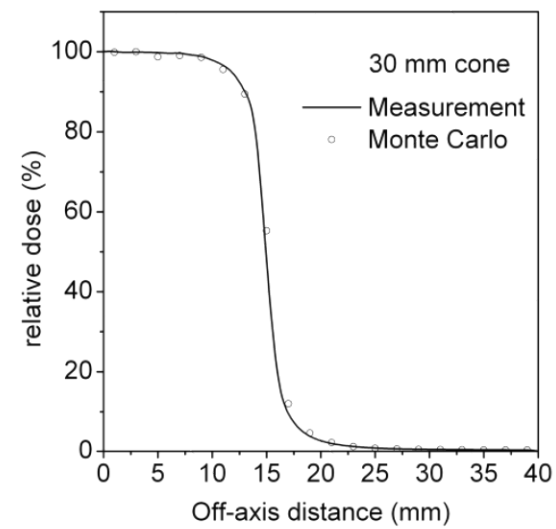
Computer Intel Quad Core Harpertown E5405 (2.0 GHz).

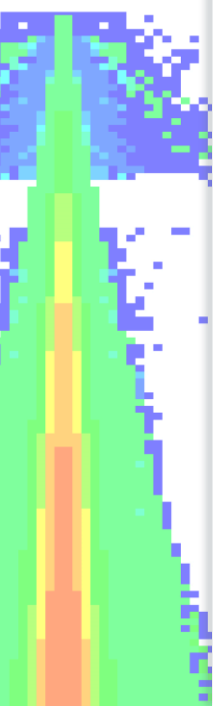
Version 2008 of PENELOPE.

Uncertainty 2% ($k = 2$):

- Cone 10 mm: 9 h.
- Cone 20 mm: 3.6 h.
- Cone 30 mm: 0.9 h.







Conclusions

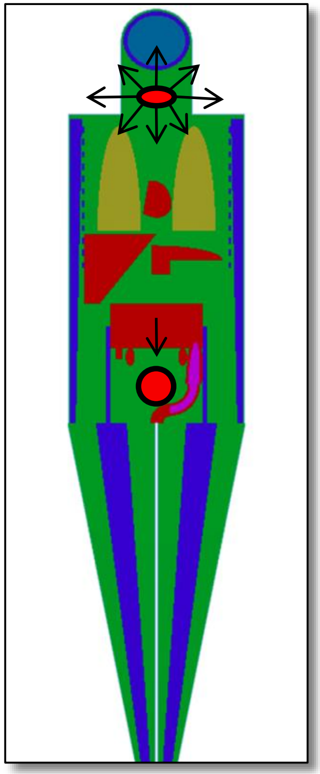
We have developed an optimization algorithm based on ant colonies that allows the efficient implementation of variance reduction techniques in different situations.

It makes use of information registered on importance maps.

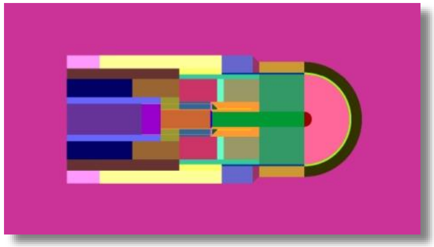
Minimum intervention by the user is required.

Other applications

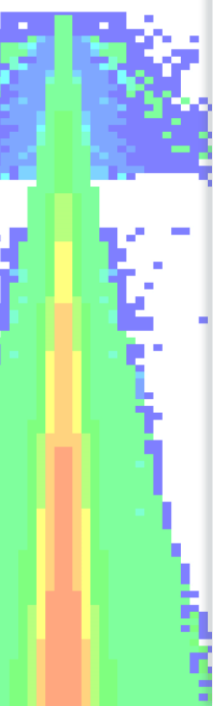
In addition to the former situations, the optimization algorithm has been applied in solving other problems:



- Calculation of specific absorbed doses to organs by nuclear medicine procedures. Efficiency × 10.
- Computation of correction factors of micro-ionization chambers. Efficiency × 100.



Perspectives



- Application of the optimization algorithm to other problems that use the Monte Carlo simulation of radiation transport.
- Implementation in other simulation codes.
- To increase the degree of automation.
- Study of applications of the information stored in the importance maps.

Papers

1. García-Pareja S, Vilches M, Lallena AM. Ant colony method to control variance reduction techniques in the Monte Carlo simulation of clinical electron linear accelerators. Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2007;580(1 Spec. Iss.):510-3.

2. Carvajal MA, García-Pareja S, Guirado D, et al. Monte Carlo simulation using the PENELOPE code with an ant colony algorithm to study MOSFET detectors. Physics in Medicine and Biology. 2009;54(20):6263-76.

3. García-Pareja S, Vilches M, Lallena AM. Ant colony method to control variance reduction techniques in the Monte Carlo simulation of clinical electron linear accelerators of use in cancer therapy. Journal of Computational and Applied Mathematics. 2010;233(6):1534-41.

4. García-Pareja S, Galán P, Manzano F, et al. Ant colony algorithm implementation in electron and photon Monte Carlo transport: Application to the commissioning of radiosurgery photon beams. Medical Physics. 2010;37(7):3782-90.

5. Cenizo E, García-Pareja S, Galán P, et al. A jaw calibration method to provide a homogeneous dose distribution in the matching region when using a monoisocentric beam split technique. Medical Physics. 2011;38(5):2374-81.

6. Díaz-Londoño G, García-Pareja S, Salvat F, et al. Monte Carlo calculation of specific absorbed fractions: Variance reduction techniques. Physics in Medicine and Biology. 2015;60(7):2625-44.