Optimization of Monte Carlo medical linac simulation in photon mode

Elaboration of virtual source models

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Outline

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- Principle : destruction of cancer cells DNA → Radiation // matter interaction.
- Based on the use of :
  - medical imaging,
  - Numerical beam modeling and dose distribution calculation.
  - Linac beam.
- High precision → use of Monte Carlo calculations.

  Long computation time.

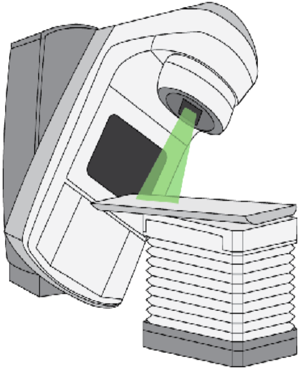

Figure 1: Medical electron linac used for e-/x-ray beams.

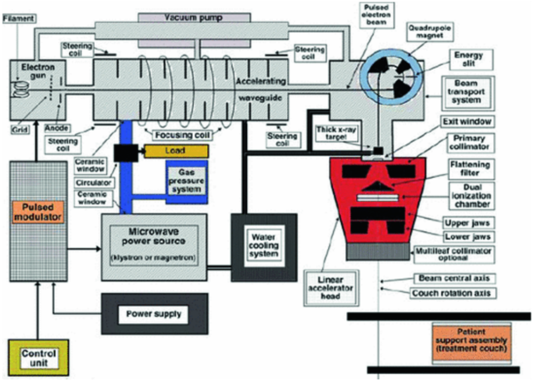

Figure 2: Medical linac components [1].

[1]Podgoršak E.B. (2016) Particle Accelerators in Medicine. In: Radiation Physics for Medical Physicists. Graduate Texts in Physics. Springer, Cham. https://doi.org/10.1007/978-3-319-25382-4_14

Outline

Medical linac Monte Carlo simulation techniques

Three main methods :

- Direct modeling of the linac head (classic approach).
- Use of pre-calculated phase space (ex : IAEA database).
- Developement of virtual source models.

- Detailed modelling of the linac head geometry
- Accurate approach but also sensitive to :
  - geometry modelling / materials
  - simulation parameters
    - number of primaries
    - electron beam parameters
    - cut-off for $h\nu / e^{-} / e^{+}$
- Disadvantage : **simulation is too time consuming ..**

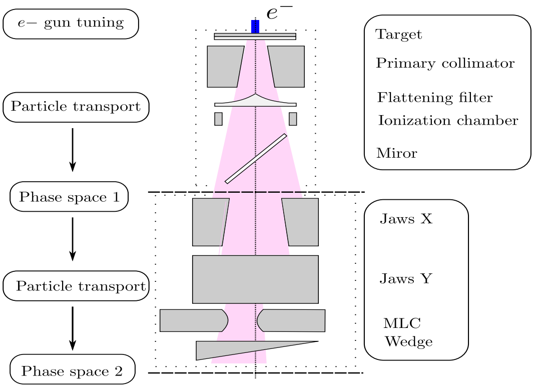

Figure 3: Visualisation of a benchmark linac head geometry.

- Linac simulation is split into 2 parts :
  1. Simulation of the patient independent part :
     - model the linac geometry (mainly beam target, the primary collimator, the vacuum window and the flattening filter)
     - storage the beam properties in a raw data file : phase space file.
  2. Simulation of patient dependent part
     - use the phase space as primary participles generator.
     - set the secondary collimator for a specific radiation field.
     - particle transport through a voxelized phantom.
- A standard phase space contains information about particles :
  - the position (x, y, z),
  - the direction (u, v, w),
  - the Energy E
- Disadvantage : **Large storage requirements are needed ..**

- The linac beam fluence $\Phi(x, y, z, u, v, w, E)$ is represented by the sum of multiple virtual sources :

$$\Phi(x, y, z, u, v, w, E) = \sum_{i=1}^{n} f_i . \Phi_i(x, y, z, u, v, w, E) \quad (1)$$

- **Advantages :**
  - No need for geometrical linac head information.
  - No need for huge data storage.
  - Unlimited and independent particle generation
  - Fast simulation to achieve a certain statistical uncertainty

Outline

Our VSM approach

Variable	Meaning	Type of variable
X	First coordinate (usually X position in cm)	Real*4
Y	Second coordinate (usually Y position in cm)	Real*4
Z	Third coordinate (usually Z position in cm)	Real*4
U	First direction cosine	Real*4
V	Second direction cosine	Real*4
E	Kinetic energy in MeV	Real*4
Statistical_Weight	Particle statistical weight	Real*4
Particle_type	Type of the particle *Current list:* photons, electrons, positrons, protons and neutrons	Integer*2
Sign_of_W	Sign of W (Third direction cosine)	Logical*1
Is_new_history	Signifies if particle belongs to new history	Logical*1
Integer_extra	Extra storage space for integer variables *Currently defined variables:* Incremental history number EGS LATCH PENELOPE ILB	n*(Integer*4) ($n \geqslant 0$)
Float_extra	Extra storage space for real variables *Currently defined variables* XLAST YLAST ZLAST	m*(Real*4) ($m \geqslant 0$)

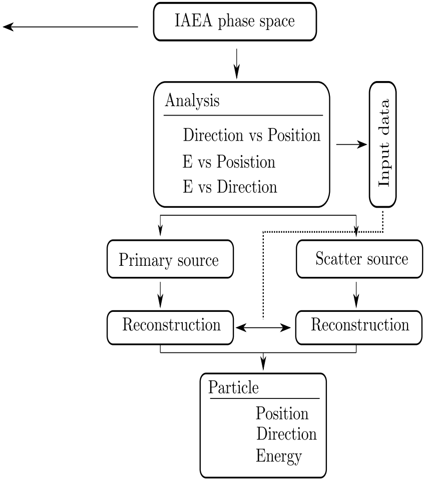

Figure 4: IAEA phase space analysis and VSM decomposition.

- IAEA phase space $\longrightarrow$ 1D/2D correlated PDFs.
    - 1D histograms : h_E, h_ϕ
    - 2D histograms (correlations) : $h_{(R,\phi)}, h_{(E,\phi)}, h_{(\delta,E)}$ ...

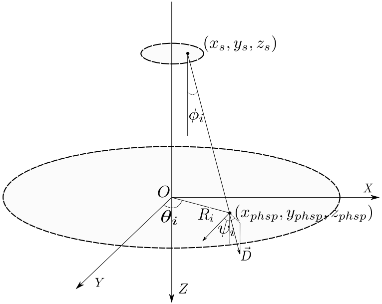

Figure 5: Beam line coordinate system

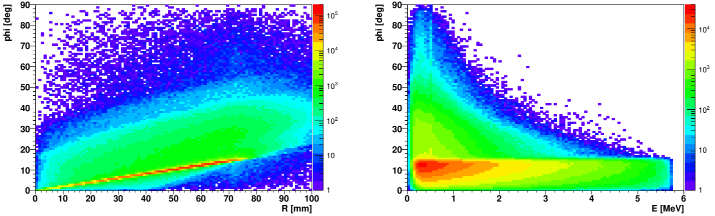

Figure 6: Analysis of the Elekta Precise photon beam phase space. (a) : correlation between R and ϕ; (b) : correlation between E and ϕ.

- $\Phi = \Phi_p + \Phi_s$
- Bremsstrahlung photons : Φ_p (60%).
- Scattered photons : Φ_s (40%)

Our VSM approach

Beam reconstruction

- `load 1D/2D (`$h^{p,s}_{E,i=1\ldots200}$`,` $h^{s}_{\phi,i=1\ldots200}$`,` $h^{s}_{\delta,i=1\ldots200}$`,` $h^{p,s}_{(x,y)}$`)`
- `sample` $\zeta \sim \mathcal{U}(0,1)$
- `if` $\zeta \leq 0.6$
  - `sample` $(x_s, y_s) \sim \mathcal{G}(0,\sigma_s) \times \mathcal{G}(0,\sigma_s)$
  - `sample` $(x_{phsp}, y_{phsp}) \sim h^{p}_{(x,y)}$
  - `calculate` (ψ,ϕ)`; define` i_ϕ
  - `sample` $E \sim h_{E,i_\phi}$
- `else`
  - `sample` $(x_{phsp}, y_{phsp}) \sim h^{s}_{(x,y)}$
  - `calculate` (R,θ)
  - `define` i_R `and sample` $\phi \sim h^{s}_{\phi,i_R}$
  - `define` i_ϕ `and sample` $\delta \sim h^{s}_{\delta,i_R}$
  - `calculate` ψ`.`
  - `sample` $E \sim h^{s}_{E,i_\phi}$
- `return` $p(R,\theta,\psi,\phi,E)$

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VSM validation and results (Zakaria Aboulbanine and Naïma El Khayati 2018 Phys. Med. Biol. 63 085008)

Validation under Geant4-[mt] [1, 2]

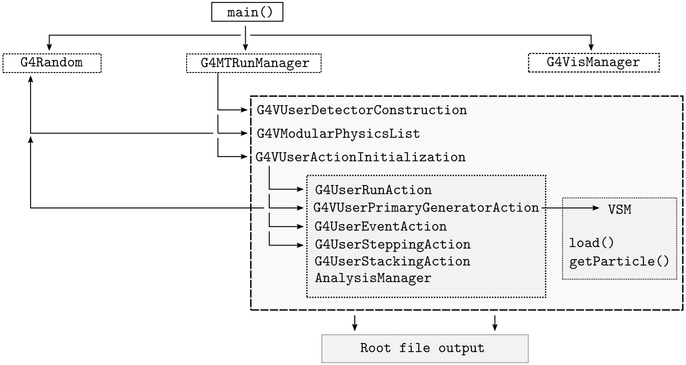

Figure 7: Basic structure of the Geant4 validation code.

Dose distribution in water

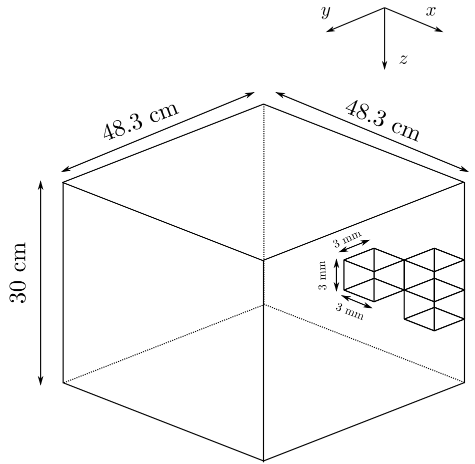

Figure 8: Voxelization of the water phantom for dose distribution calculation (placed at the center of coordinate system).

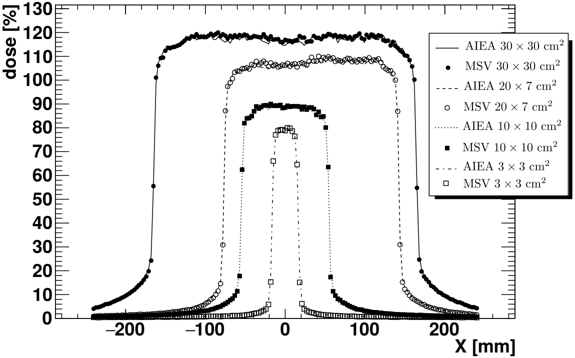

Figure 9: Dose distribution in a water phantom ($z = 10$ cm, $y = 0$ cm). lines : IAEA phase space normalised dose; markers : VSM normalised dose [3].

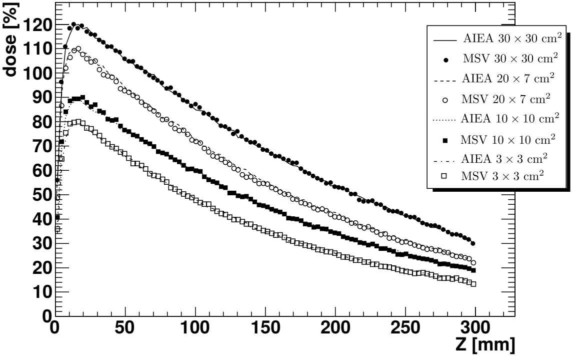

Figure 10: Dose distribution in a water phantom $(x = y = 0)$ cm. lines : IAEA phase space normalised dose; markers : VSM normalised dose [3].

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References

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