GATE 8.0 – Tissue Equivalent Proportional Counter actor

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The tissue-equivalent proportional counter (TEPC) is a detector dedicated to the measurement of the lineal energy transfer (LET) distribution in a volume at the micrometric scale. These physical data, depending on the beam quality and the location of the detector in the beam, is mainly used to calculate the biological dose for high LET radiation and to characterize the beam quality for radioprotection issues.
A TEPC is very similar to a classical gas ionization chamber. The major difference relies in the sensible volume, which is spherical and filled with low pressure tissue-equivalent gas instead of air. These characteristics allow the TEPC to mimic the shape and composition of the tiny structures in a cell nucleus (about 1 µm of diameter).

1. Quick use

The principle of the TEPCactor is the same as the EnergySpectrumActor, except that the frequency of lineal energy is stored instead of the deposited energy. In order to obtain the lineal energy, the deposited energy is divided by the mean chord of the TEPC volume ($\bar{L} = \frac{2}{3}\pi\,\phi_{TEPC}$). **This imposes creating a sphere as geometry for the TEPC.**

Generic commands – The following commands allow to create, attach and save the result in a ROOT file (and a .txt file, if necessary):

```
/gate/actor/addActor TEPCActor      myTEPC
/gate/actor/myTEPC/attachTo         myDetector
/gate/actor/myTEPC/saveAsText       true
/gate/actor/myTEPC/save             output/myLETspectrum.root
```

Pressure command – The pressure of the tissue-equivalent gas (propane-based material) is used to tune the size of the water equivalent sphere represented by the TEPC detector. In the literature, the density of such materials is generally defined for standard pressure and temperature conditions. Although the user can directly create a low pressure and density gas material in the "*data/myGateMaterial.db*" file, the following command allows to modify in-line the pressure in the TEPC material if this one is defined for standard pressure and temperature conditions:

```
/gate/actor/myTEPC/setPressure      0.044 bar
```

Output commands – This list of commands makes it possible to change the scale of the LET distribution in order to correctly fit with the expected results. As the lineal energy distribution generally extends on several orders of magnitude, the default option is the logarithmic scale:

```
/gate/actor/myTEPC/setLogscale      true
/gate/actor/myTEPC/setNumberOfBins 150
/gate/actor/myTEPC/setEmin          0.01 keV
/gate/actor/myTEPC/setNOrders       6
```

This could be replaced by a linear scale:

```
/gate/actor/myTEPC/setLogscale      false
/gate/actor/myTEPC/setNumberOfBins 150
/gate/actor/myTEPC/setEmin          0 keV
/gate/actor/myTEPC/setEmax          100 keV
```

The last command allows to normalize the distribution by the number of incident particles:

```
/gate/actor/myTEPC/setNormByEvent  true
```

2. Example

An example of a TEPCactor use is provided in the example repository. In this example, a TEPC detector is placed at different positions in a water tank and irradiated with a 155 MeV mono-energetic proton beam. This setup was used to validate the results against the TEPC measurements published by [Kase et al. 2013][1]. In this comparison, our key point was the optimization of the particle cuts and step limiters. Indeed, the lineal energy distribution at the micrometric scale is highly sensible to these two parameters. The particle cuts must be low enough to simulate any significant contribution in the lineal energy distribution and the step limiters must be correctly tuned in order to avoid boundary effects on geometry elements, while keeping the global simulation time as low as possible. In the following sections, we describe the geometry and the physical parameters that were tested to obtain the final macro files available in the example repository.

2.1. Simulations

The Figure 1 (A) shows the experimental setting that was modeled in Gate. A TEPC detector is placed in a water tank and is irradiated with a circular 155 MeV proton source of 50 mm in diameter. The entrance of the sensible volume of the TEPC, which is the effective measurement point of the detector, is successively placed at a depth of 50 mm (plateau region of the Bragg curve) and at a depth of 160 mm (3 mm before the Bragg peak depth).

The Figure 1 (B) shows the Gate geometry corresponding to the TEPC. The gas cavity of the TEPC is filled with a mix of propane, CO_2 and N_2 with a pressure of 44 mbar in order to emulate a sphere of tissue equivalent to 1 µm in diameter. The wall is composed of A-150 plastic. In order to optimize the production of particles in the TEPC, the wall was subdivided into 4 layers with decreasing production cut values for electrons, positrons, gammas and protons. From the outer layer to the inner one, the couples {width/cut/stepLimiter} are $\{1.159/10^{-1}/10^{-1}\}$ mm, $\{10^{-1}/10^{-2}/10^{-2}\}$ mm, $\{10^{-2}/10^{-3}/10^{-3}\}$ mm and $\{10^{-3}/10^{-4}/10^{-4}\}$ mm. We can note that the stepLimiter parameter only impacts the protons.

Three sets of parameters are studied for both plateau and Bragg peak positions: the production cuts in the wall, the production cuts in the gas cavity and the step limiters in the wall. Each simulation was performed using a single CPU (Intel® Xeon® CPU E5-2690 3GHz) with 10^7 incident protons. We used the TEPCactor to obtain the lineal energy frequency *f(y)* (where *y* is the lineal energy expressed in keV/µm), we normalized the distribution and we stored the simulation time.

[1] **Kase et al.** – Microdosimetric calculation of relative biological effectiveness for design of therapeutic proton beams, *Journal of Radiation Research*, 2013, 54, 485–493

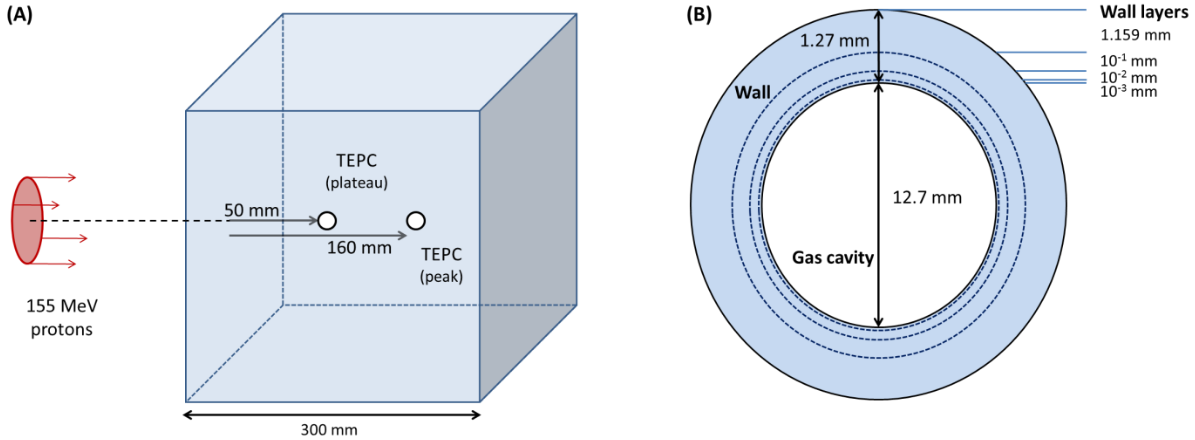

Figure 1: Experimental setting (A) and geometry of the TEPC detector (B) simulated with Gate. The wall of the TEPC is subdivided in 4 layers with decreasing thicknesses.

2.2. Results

Production cuts in the wall – The Figure 2 shows the comparison between the distributions obtained for uniform production cuts values in the wall and the optimal configuration with layers (Figure 1 (B)). The step Limiters are deactivated (value of 10 m) and the production cut in the gas cavity is set to 1 mm. We can see that, for both positions in the water tank, significant contributions in the distribution are coming from the wall. It is then necessary to set this cut as low as possible (a value of 10^{-4} mm allows to reach the physical limit of Geant4 with the 'empenelope' physicsList (100 eV)). We can also see that the optimal cut configuration allows obtaining the same results. The simulation time for a cut of 10^{-4} mm and for the optimized wall are respectively 55.3 and 1.7 hours, with a gain in time of a factor 32.

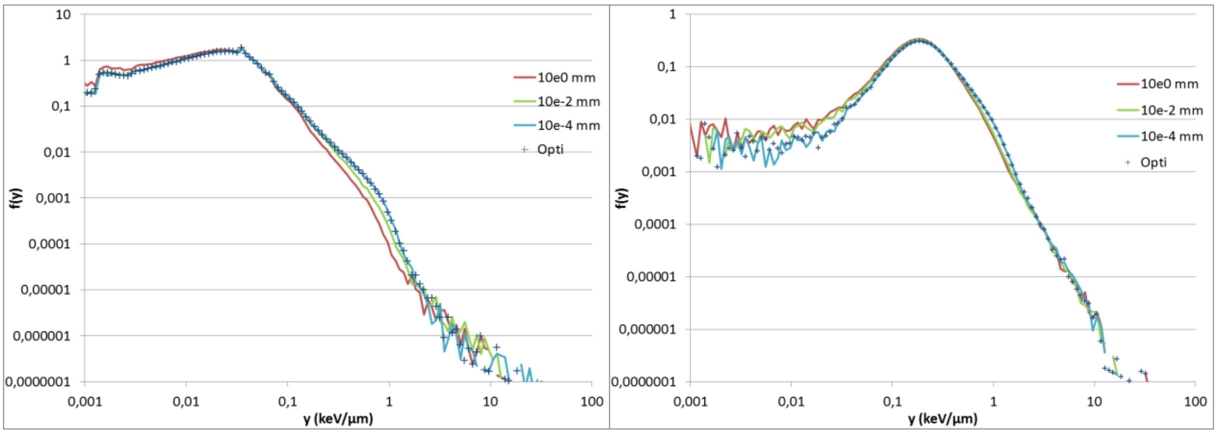

Figure 2: Distributions for uniform production cut values in wall and the optimal configuration for the plateau region (left) and the Bragg peak region (right). Step limiters are deactivated and production cut in the gas is set to 1 mm.

Production cut in the gas – The Figure 3 compares the distributions obtained for a 1 mm and a 10^{-4} mm production cut in the gas cavity. The step limiters are not activated and the production cuts in the wall are optimized. We can see no significant differences between the distributions for both plateau and peak regions. Then, we can conclude that there is no particle created in the cavity with a sufficient energy to escape from this volume. As simulation times are equivalent (1.7 hours), we choose to keep the 10^{-4} mm production cut. Indeed, this result was specific to the 155 MeV proton beam. Additional simulations with 300 MeV/u carbon ions showed that many particles created in the cavity can escape from this volume.

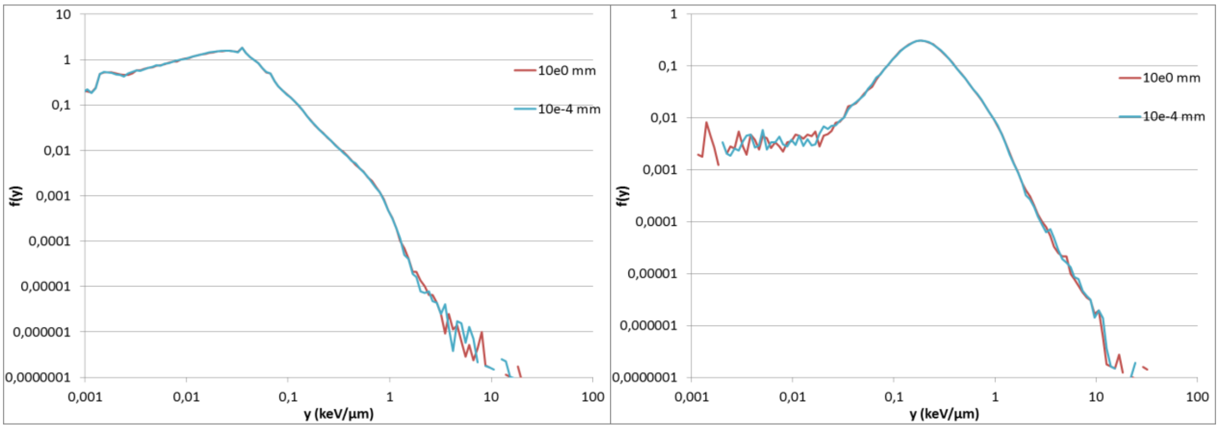

Figure 3: Distributions for a high and a low production cut in the gas cavity for the plateau region (left) and the Bragg peak region (right). Step limiters are deactivated and production cuts in the wall are optimized.

StepLimiter in the wall – The Figure 4 shows the comparison between lineal energy distributions without stepLimiter, with a stepLimiter of 10^{-1} mm and with the optimized stepLimiters (see section 2.1. Simulations). We can see that the only situation leading to a smooth distribution is the optimized one. As the stepLimiter parameter is generally used to increase the precision of the depth dose profile of charged particles, we tested different step limiters for the water tank region. All the results in terms of lineal energy distribution in the TEPC are smooth.

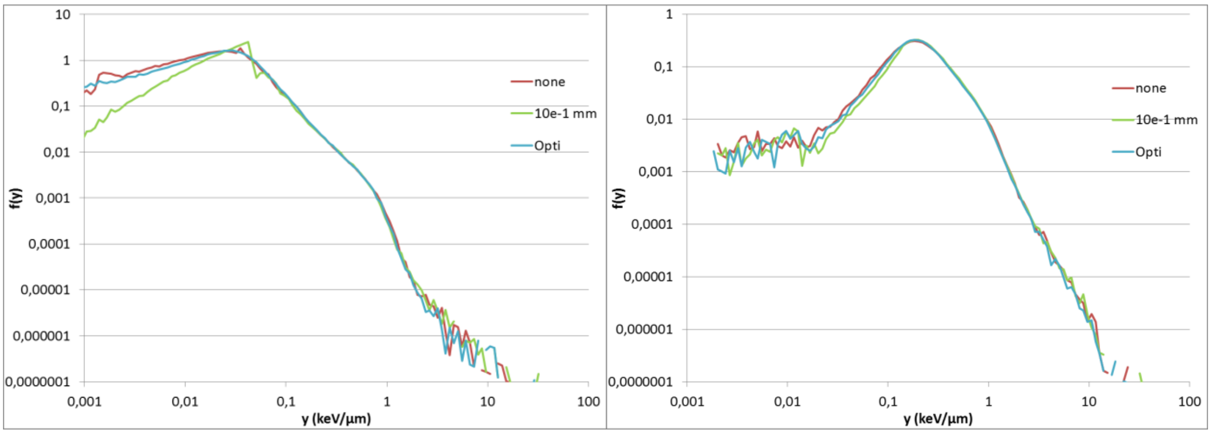

Figure 4: Distributions for uniform and optimized step limiters in the wall of the TEPC for the plateau region (left) and the Bragg peak region (right). The production cuts in the wall are optimized and the production cut in the gas is set to 10^{-4} mm.

2.3. Conclusion

In order to simulate the correct lineal energy distribution, the user should be aware that the physical events occurring in a TEPC detector extends on a very large range of energy. Interactions in the TEPC wall can lead to an increased number of events in the gas cavity. The particles created in the gas cavity and escaping from it can also lead to a modification of the lineal energy distribution. Additionally, the choice of the correct production cuts and step limiters is a crucial point regarding the simulation time. In this example, the gain between the simple and the optimized configuration was about 30 for computing time. Finally, the proposed TEPC configuration constitutes a good start point for the simulation of the lineal energy distribution of any clinical proton or carbon ion beam.