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An algorithm to optimize the tracking of ionizing particles

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Abstract

We describe a way to simulate electromagnetic showers, automatically optimising the number of tracks which need to be simulated, in order to obtain the same physics results as a full shower simulation. This method is implemented in Geant4.

1 Introduction

It is well known that in a few electromagnetic processes (ionisation and bremsstrahlung) we need to define a low energy cutoff for the production of secondary particles. This feature introduces an arbitrary limit between two models of simulation (see paragraph 4 below).
Indeed several physics quantities, like the distribution of the energy released by a charged particle along its trajectory, are independent of that limit. Some others, like the total track length in the shower development or the energy flux across boudaries, may be sensitive to the energy cutoff.
Using the algorithm described in this note has the following benifits:

1. it make those quantities less dependent on the choice of the cutoff,
2. it gains performance by optimising the number of tracks to be simulated.

2 A reminder: the range of a charged particle

A particle of energy E moving in a material loses its energy. The range of the particle is the distance that the particle will travel until it releases all its kinetic energy. Given the density of energy released along the trajectory, f(e), the range of the particle is:

$$R(E) = \int_{\epsilon=E}^{0} \frac{1}{(f\epsilon)}\, d\epsilon$$

In Geant4 we systematically exploit the relation between energy and range: E $\longleftrightarrow$ R(E)

3 The concept of the safety radius

Given a point in a detector, the geometry navigator implements the concept of safety and provides other information. The safety is the radius of a spherical region which is guaranteed to be wholly contained inside the current volume.
The tracking and the physics processes can exploit this information. If the energy of a particle is such that its range is smaller than the safety radius, the particle will stop in the current volume anyway. If the range is larger than the safety radius the particle can leave the volume and reach another component of the detector, for instance a detection gap. Therefore we can use this comparison to decide if it is worthwhile, or not, to continue the simulation of that particle.

4 Simulation of an ionising particle

The probability, for a charged particle of energy E moving in a material, to shoot an electron (a delta-ray) of kinetic energy t increases for t $\longrightarrow$ 0. In other words, the charged particle has a quasi-infinite probability to emit an electron of null energy.
To overcome this difficulty one must fix a lower limit for the energy of the produced delta-rays: t_{cut}(let call it the default production threshold). One generates only the delta rays above that threshold. The delta rays below the threshold are taken into account by a mean energy released by the ionising particle along its trajectory.
In addition, for efficiency reasons, the cross section for producing delta rays above t_{cut}, $\sigma(E, t_{cut})$, and the mean energy loss by the ionising particle, $dE/dx(E, t_{cut})$, are tabulated at initialisation phase as a function of E, the energy of the ionising particle. Those tables are dependent on t_{cut}.
An obvious consequence of this procedure: one cannot create delta rays below $t_{cut}$from these tables.

5 Production of delta rays near a volume boundary

When a ionising particle is near a boundary, even the delta rays of very low energy can escape the boundary, reach another part of the detector which could be sensitive, and therefore contribute to the response of the detector. In conclusion, in many circumstances it is meaningful to create explicitly those delta rays, even if they have low energy.

With the traditional simulation (the procedure explained in section 4) the only way to produce the delta rays with the lowest possible energy is to build the σ and dE/dx tables with

the lowest possible t_{cut}. This procedure will generate plenty of delta rays along the full trajectory of the ionising particle, even where this generation is undesirable.

The algorithm we describe below allows us to keep t_{cut}as high as possible, and to generate low energy delta rays only where they are needed, i.e. near the boundaries. The result can be a drastic improvement of the performance of the simulation, keeping the same quality of physics results as with the lowest cut.

The tables are built as explained in section 4. Let us call rcut the range corresponding to default energy threshold t_{cut}. Our fundamental principle is the following: at a given point, if the safety radius is smaller than r_{cut}one has to produce additional delta rays. The energies of these delta rays will correspond to ranges between safety and r_{cut}, since those delta rays can escape a boundary.

1. In fact the delta rays are emitted along the step of the ionising particle. The safety radius along the step is evaluated, as a first implementation, using the spherical safety at beginning and at the end of step: saf1 and saf2. (To be general, it should be evaluated as a cylindrical or toroidal safety along the step).
2. If the minimal safety is smaller than r_{cut}we generate additional delta rays along (a fraction of) the step of the ionising particle.
3. The number of delta rays to be emitted are calculated using an approximate formula based on the differential cross section of the delta ray production.
4. The energies of the delta rays start from the energy corresponding to minimal safety, and end at an upper limit of t_{cut}, with a distribution proportional to $1/t^2$.
5. The energies of the delta rays are substracted from the contribution of the continuous part of the ionising particle, avoiding a double counting of the energy released by the ionising particle along its step.
6. The positions of the delta rays along the step are uniformly distributed along a fraction of the step which is determined by the relative values of saf1, saf2 and r_{cut}. (The reason for using a uniform distribution is that, in first approximation, the cross section for delta rays production is constant along the step).

6 An example

case1

In figure 1 a proton of 500 MeV passes through a block of 5 cm of iron. The production threshold is r_{cut}= 1 mm, which corresponds to t_{cut}= 1.25 MeV in iron. Which such a threshold there are no delta rays produced in iron.
In fact, in this picture, 100 protons are superimposed, the multiple scattering is off.
The distribution of the energy deposited in iron is shown in figure 4, with a bigger statistic and multiple scattering included.

case2

In figure 2, protons, with the same energy. The delta rays production threshold is r_{cut}= 10 micron (t_{cut}= 58 keV). The delta rays are emitted along the proton trajectory. The distribution of the vertex position can also be seen in figure 5.
The distribution of the energy deposited in iron is shown in figure 4.
The delta rays created at the end of the block of iron can escape the boundary and travel in the gas behind iron. The energy spectrum of those delta rays when leaving iron is in figure 6: it is the energy flux behind the block of iron.

case3

In figure 3, r_{cut}= 1 mm as in case 1, but the algorithm described in this note is applied. The delta rays in iron are not created, except those near the boundaries. The distribution of the

vertex position can also be seen in figure 5. The energy deposited in iron is in figure 4.
The energy flux behind the block of iron is shown in figure 6. It is the same as in case 2.

The three cases give the distribution of energy deposit in iron. But only the cases 2 and 3 can simulate the energy flux behind the block of iron. Concerning the performance, in this example, case 3 is about 10 time faster than case 2.

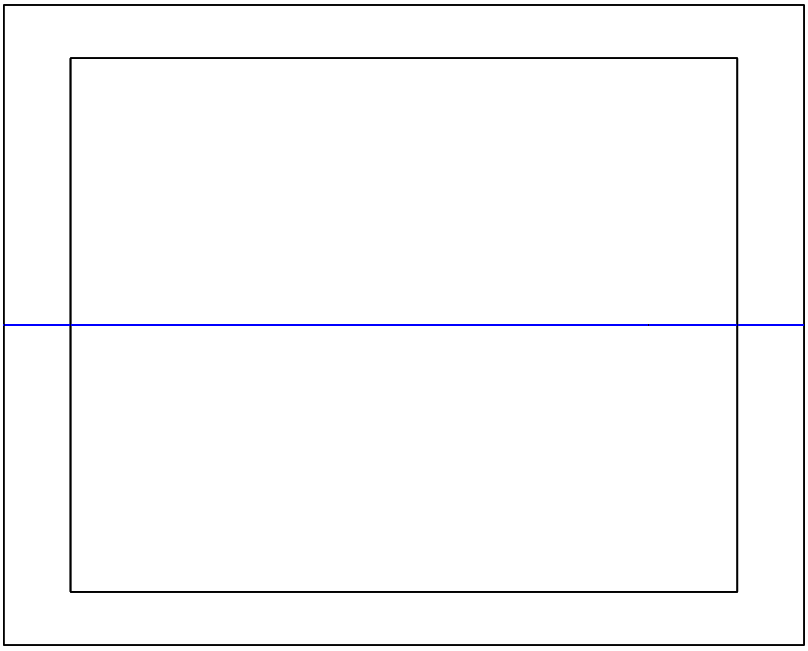

Figure 1: case 1: 100 protons of 500 MeV in Iron, using traditional simulation with $r_{cut} = 1mm$.

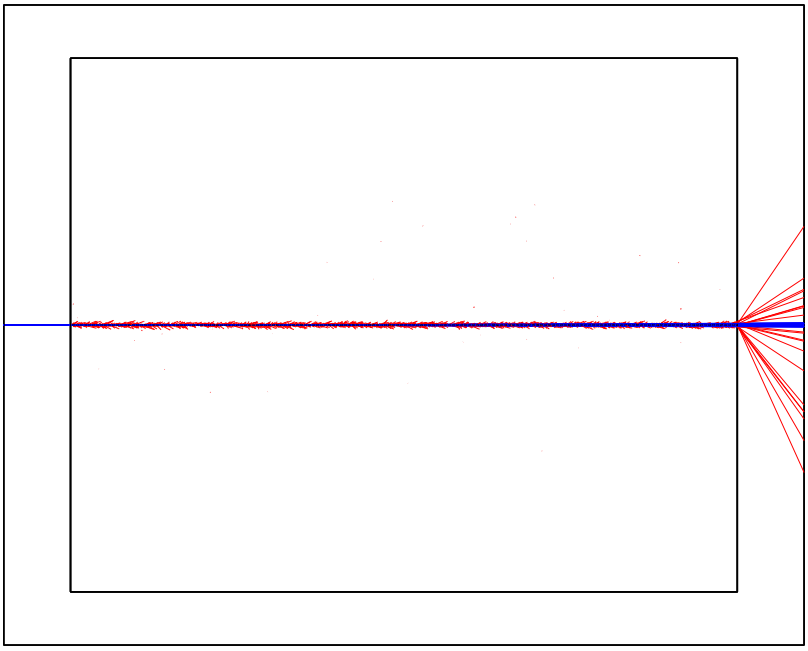

Figure 2: case 2: 100 protons of 500 MeV in Iron, using traditional simulation with $r_{cut} = 10\mu$

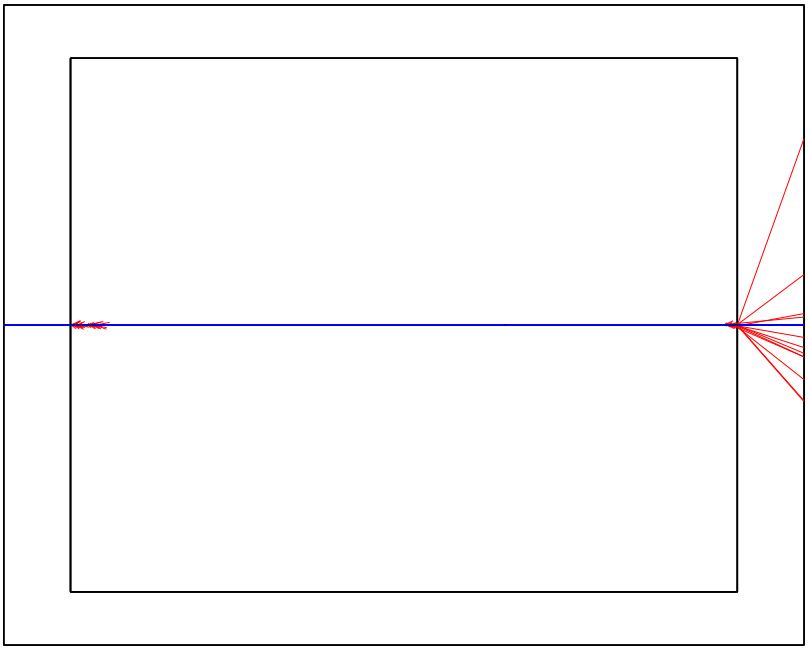

Figure 3: case 3: : 100 protons of 500 MeV in Iron, using our new algorithm with $r_{cut} = 1mm$

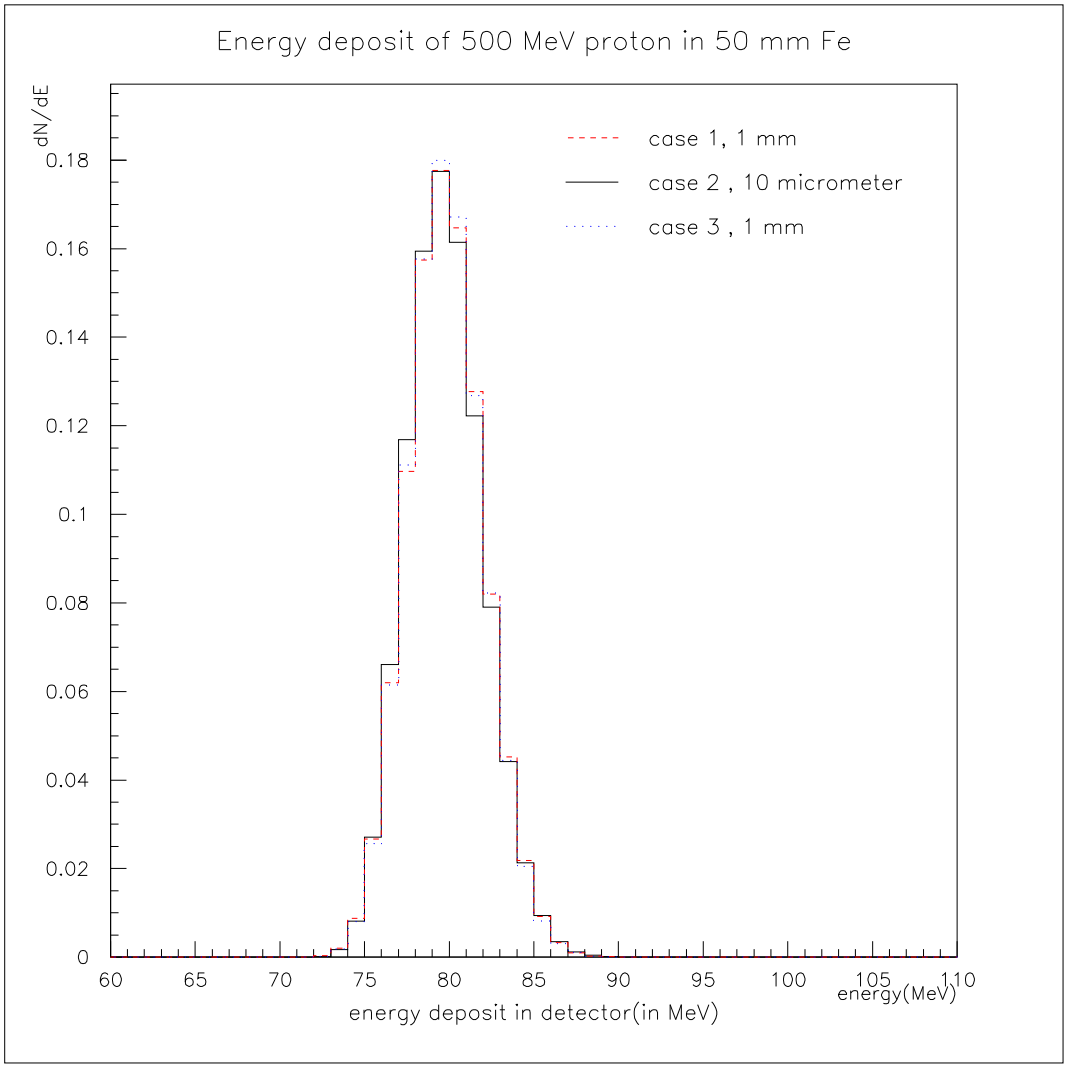

Figure 4: Energy deposit of 500 MeV protons in 50mm of Iron. Results of simulations with traditional algorithm (cases 1 and 2) and our new algorithm (case 3.)

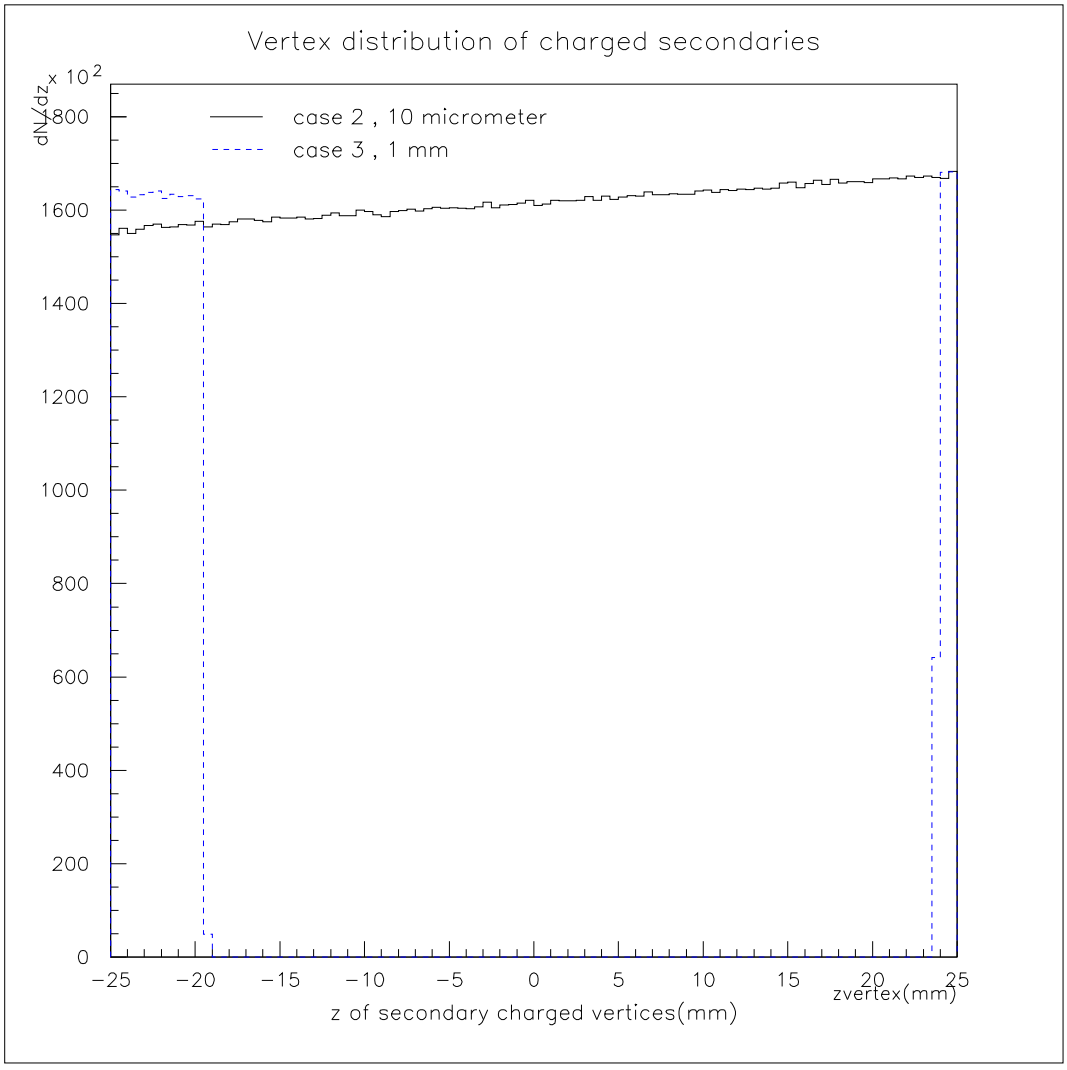

Figure 5: Vertex distribution of charged secondary particles. Results of traditional algorithm (cases 2) and our new algorithm (case 3.)

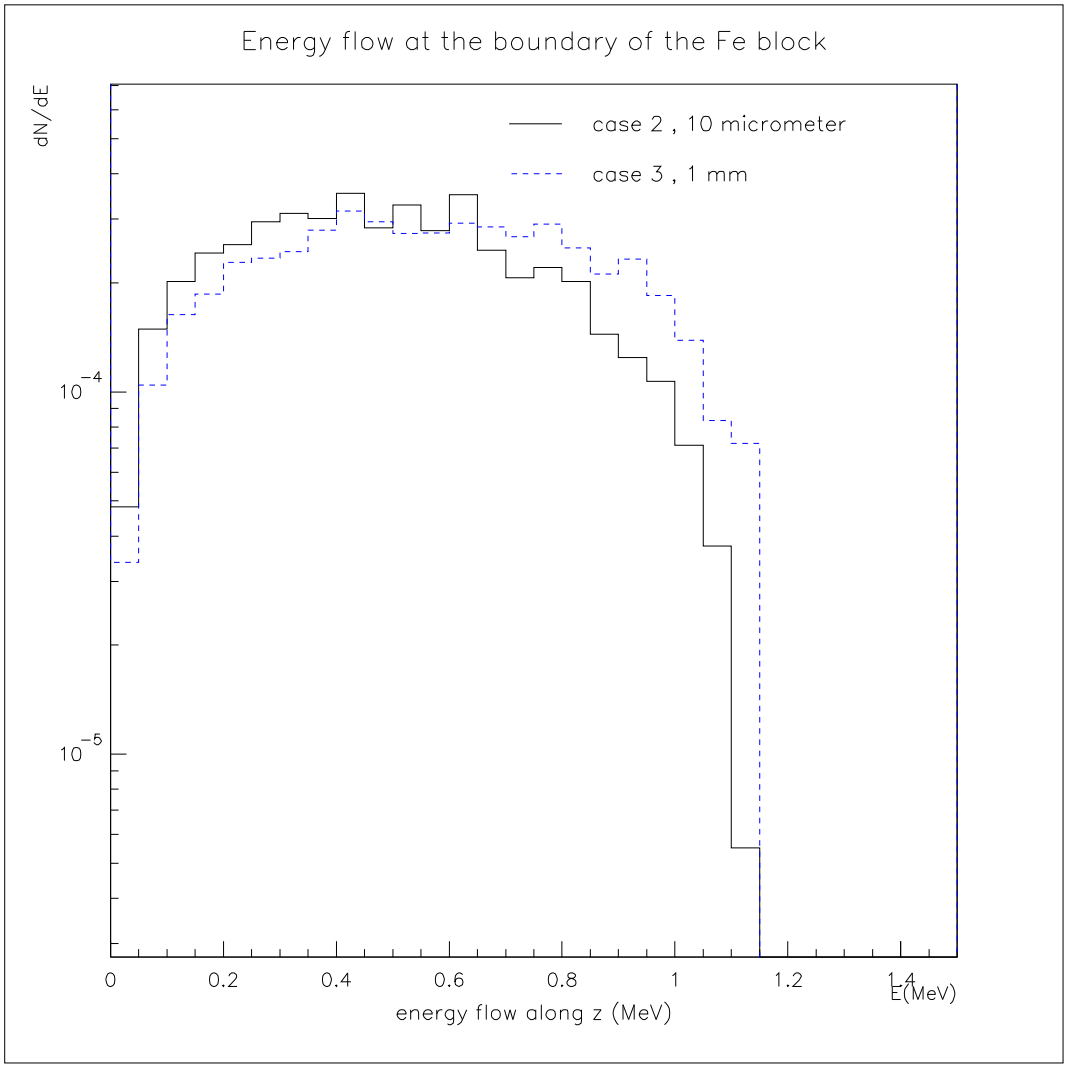

Figure 6: Energy flow at the boundary of the Iron block. Results of traditional algorithm (cases 2) and our new algorithm (case 3.)