Electric Field in Cosmos

May 19, 2016

1 Introduction

Simple but unrealistic electric fields can be used without any coding by the user. It may be used to see the basic effect of electric field on charged particle motion. If the user wants to use more realistic field effect, it is better to make the cosmos library following the procedure described in Sec.3.

In every case, the field strength must be given in unit of V/m. The final field vector, $\vec{\mathcal{E}}$, must be given in the E-xyz system.

2 Simple electric field

An electric field can be specified by referring to the height(H), distance to the shower axis (R) and time information (T) of each charged particle, where H is the height in m a.s.l, R (in m) the horizontal distance if DefofR='h' (default) or perpendicular distance if DefofR='p', T the time (in ns) spent from the starting point of the primary particle.

- If T is used, H is neglected.
- So the field is determined by H & R or T & R.
- If R is not given, only H or T is used.
- If neither H nor T is used, only R is used.
- If non of H, T, R is used, the filed will be 0.

To specify H, T, R, a variable, myEf and its components are used. For example, if the user want to give an electric field at $0 < H < 1000$ and $2000 < H < 3000$, respectively

```
myEf(1)%H1=0
myEf(1)%H2=1000
myEf(2)%H1=2000
myEf(2)%H2=3000
```

may be given in the "param" file. Corresponding field vectors may be given as

```
myEf(1)%Ef=Ex,Ey,Ez
myEf(2)%Ef=Ex',Ey',Ez'
```

where `Ex` etc are numerical values in V/m. The vectors must be given in the detector system (vertically upward direction is the $+Z$ direction. Internally, the values are converted into the ones in the E-xyz system.

The height list by "myEf" must be given from lower ones (note: the observation height list in the "param" file is given from higher to lower height order). For T, R, the same format is used. The max number of fields is 5.

To activate the specifications by "myEf", HowEfield=1 must be given. Its default is 0 which means non-existence of the electric field.

3 Arbitrary electric field

To use more realistic fields, the user must (re)make the library, after putting
`#define MYEFIELD`
in `$COSMOSTOP/cosmos/Zcondc.h`. Then, the user can define an arbitrary field with HowEfield=2. However, simple fields are still usable with `HowEfield=1`.

If the user wants to use arbitrary electric fields by giving HowEfield=2, the user must copy
`$COSMOSTOP/UserHook/cmyEfield.f`
into user's own application directory and modify the following line in chook.mk

```
objs = chook.o
```

to

```
objs = chook.o cmyEfield.o.
```

This cmyEfield.f is a template of how to define user's own electric field.

If MYEFIELD is defined as above, cmyEfield.f is necessary for successful compilation, even when the user gives HowEfield=0 or 1.

4 Basic Test Results

In the simulation, we sample lengths for various processes and select the shortest one, and if it is too large as compared to the length for which the energy loss or gain is too large ($> 1\%$ of the current energy), or too large as compared with the Larmor radius etc, the path is truncated. Since the path is short, the multiple scattering is treated independently of the $\vec{B}$ (geomagnetic field) and $\vec{\mathcal{E}}$ effect and are treated

The latter effect is taken into account by solving numerically the equation

$$\frac{d\vec{u}}{dt} = (\vec{v}, Ze(\vec{\mathcal{E}} + \vec{v} \times \vec{B})) \tag{1}$$

where $\vec{u} = (\vec{r}, \vec{p})$ ($\vec{r}$ is the position vector) and $\vec{v}$ is expressed as $\vec{p}c/E$ with E being the energy[1].

4.1 Collaboration of $\vec{\mathcal{E}}$ and $\vec{B}$

To see the basic effect of $\vec{\mathcal{E}}$ in the presence of $\vec{B}$, we first see the e$^-$ and e$^+$ motion at very high altitudes where the effect of air is neglected.

One electron of energy 30 MeV is injected from 100 km above the see level. The initial direction is set to be vertical (downwards). A uniform electric field is assumed which is directed upwards vertically, that is, it is $\vec{\mathcal{E}} = (0, 0, \mathcal{E}_z)$ in the detector system.

Figure 1 and 2 show charged particle tracks (yellow e-, red e+) for cases of $\mathcal{E}_z = 0, 10^2, 10^3, 3 \times 10^3, 10^4, 3{\times}10^4, 10^5$ V/m. The geomagnetic field direction is shown by a green arrow. As a rough measure of $\mathcal{E}$ for which the $e\mathcal{E}$ force competes with evB force, we get $\mathcal{E} \sim 10$ kV/m for $B \sim 3.3 \times 10^{-5}$ T. (Note that $Ze(\mathcal{E} + cB) = 0.2998Z(\mathcal{E} + cB)$ GeV/c/s, where $\mathcal{E}$ is in V/m, B in T, c in m/s).

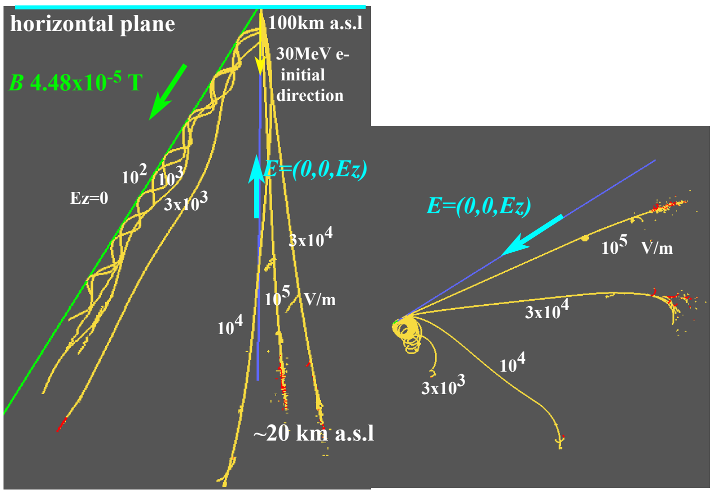


Figure 1: 30 MeV electron case. Right one is $\sim \vec{B}$ direction view. The electrons travel down to ~ 20 km where some cascading starts.

[1] See memo, Sec.??(p.??) in Appendix for numerical calculations. If $\vec{\mathcal{E}} = 0$, the exact solution is available for constant v and $\vec{B}$, which is valid in a short path.

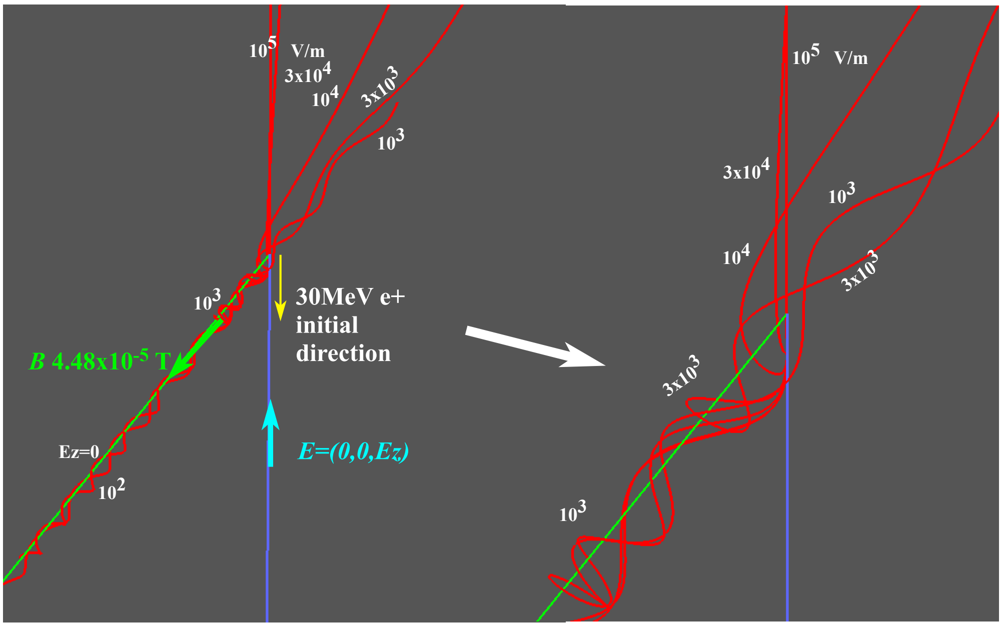


Figure 2: 30 MeV positron case. Right one is to show how the tracks bounce.

4.2 Acceleration and deceleration

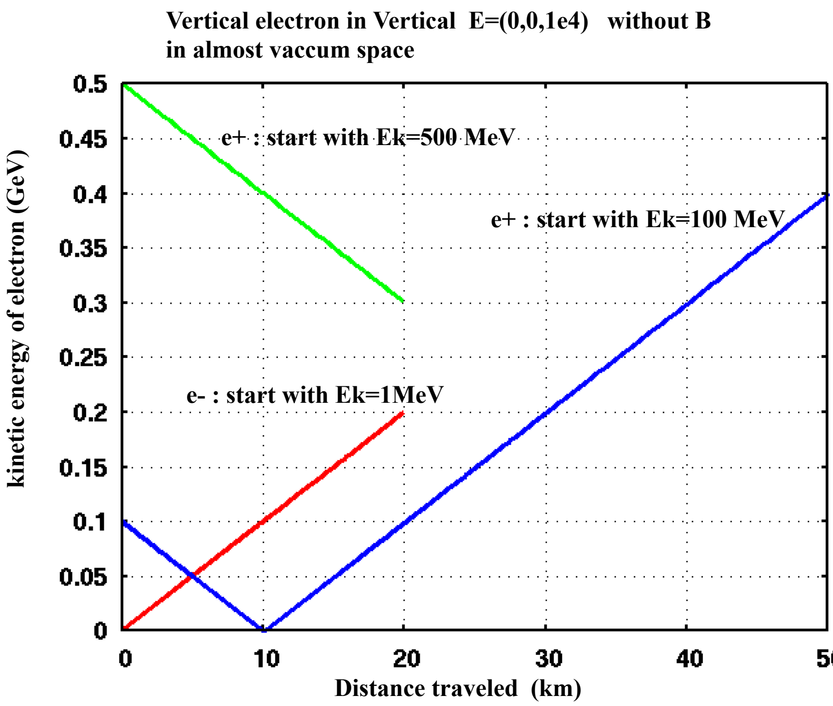


Figure 3: Distance is the length where the acceleration/deceleration is applied by 10 kV/m field. Green line: deceleration of e^+ from 500 MeV to 300 MeV. Red line: acceleration of e^- from 1 MeV to 200 MeV. Blue line: Deceleration followed by acceleration of e^+ of 100 MeV.

By putting $\vec{B} = 0$ (HowGeomag=22, MagN=0, MagE=0, MagD=0) and $\mathcal{E}_z = 10$kV/m in the the previous environment, we can see acceleration of electron and deceleration of positrons clearly. Note that in Fig.3 the vertical axis is kinetic energy but not the gain or loss (ΔE) of energy. Therefore, the linear relation which seems to hold everywhere is fake. For example, if we enlarge the red line near the origin, we see it does not go to 0 energy but is saturated at 1 MeV which is the initial energy we set; linearity with distance hold when the distance becomes > 1km.

4.3 In air

In actual cases where presence of air is normally expected, charged particles lose energy by ionization. If the $\vec{\mathcal{E}}$ acceleration is directed to the particle $\vec{v}$, the energy loss tends to be compensated and in a strong field, particle energy may increase.

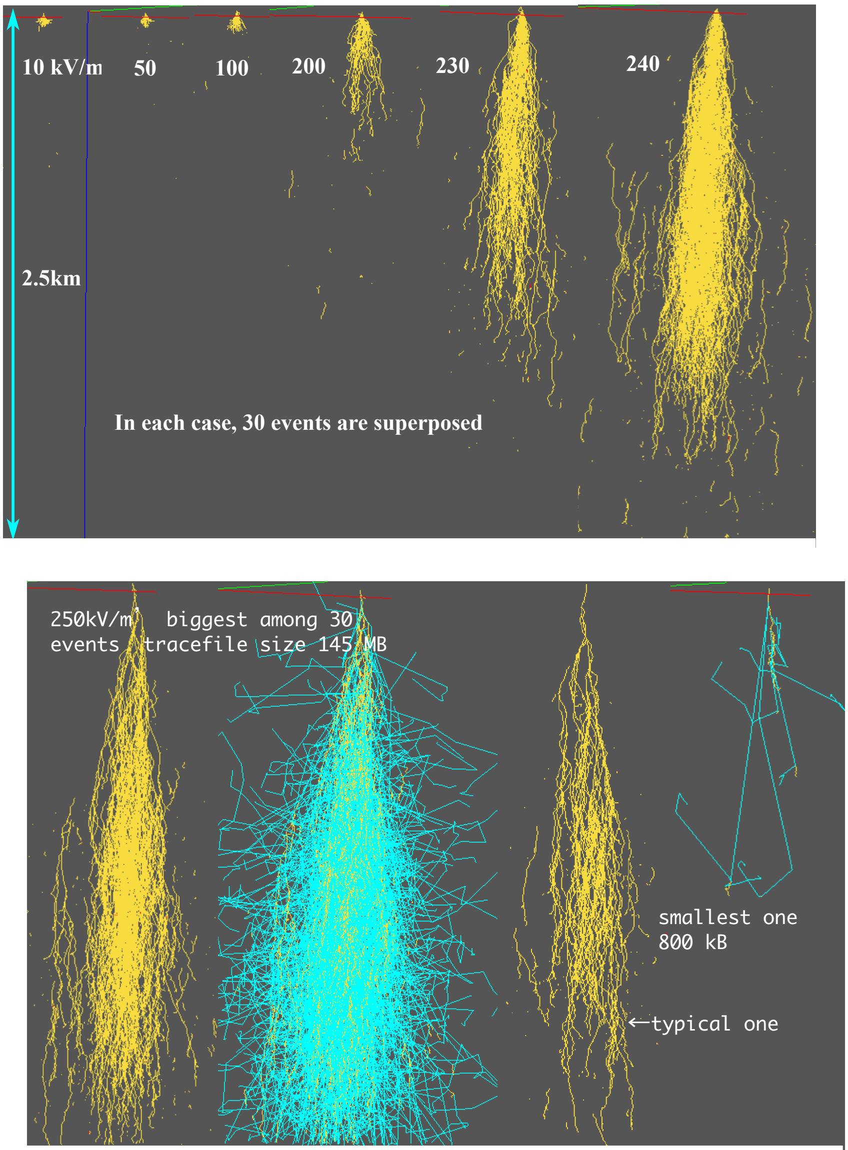


Figure 4: Upper figures show tracks of superposed 30 events for each $\mathcal{E}_z$; from left to right, 10 kV/m to 240 kV/m. Lower ones show examples of the biggest, smallest and a typical average shower among 30 showers generated in 250 kV/m field. The second one is the same shower as the first one but with photon tracks indicated by cyan lines. The smallest one is also with photon tracks; relatively high energy bremsstrahlung photon penetrates deep into the atmosphere where $\mathcal{E}_c$ is already high and no big cascading happens.

Taking $dE/dx \sim$2 MeV/(g/cm^2), a rough measure of $\mathcal{E}$ by which the energy loss is compensated is $2 \sim Z\mathcal{E}_c 10^{-8}/\rho$, i.e,

$$\mathcal{E}_c = 200 \times 10^3 \rho/Z \ \ \mathrm{kV/m} \tag{2}$$

where ρ is the density of atmosphere in g/cm^3. For $\rho = 10^{-3}$ (at height of $\sim$ 2km) and $Z = 1$, we get $\mathcal{E}_c \sim 200$ kV/m.

In Fig.4.3, an electron of 10 MeV is vertically injected from 2.5 km a.s.l. Uniform up going vertical $\mathcal{E} = (0, 0, \mathcal{E}_z)$ is assumed.

Up to $\mathcal{E}_z$ ~50 kV/m, difference from no field case is small. In big ones, shower spread due to multiple scattering and outgoing photons extends to $\sim$ 1 km.

4.4 Strong field

As we see, the $\mathcal{E}$ field effect becomes remarkable as if there were threshold around 200 kV/m (at altitudes $\sim$ 2 km). If we change $\mathcal{E}$ to 260 kV/m in the condition of the previous section[2] , we easily see that some of events become too huge and we need almost infinite computation time. This happens due to that scattered photons which even go backwards make Compton scattering and a produced electron makes another big cascading since the height of such an event could be high where $\mathcal{E}_c$ is low. This process may be repeated, and the shower extends to peripheral regions; the normal shower spread is order of 1 km at most, but in this case, big cascading happens even at few km from the core.

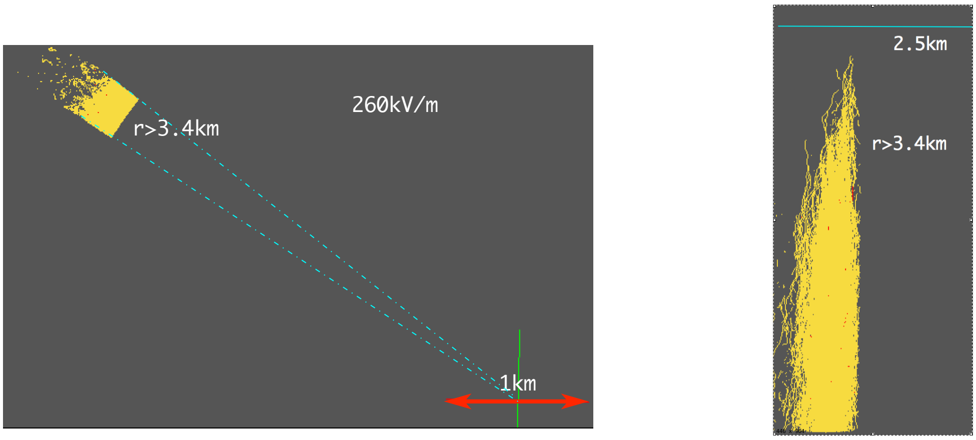


Figure 5: Example of explosive cascading far from the core. left: top view, right: side view. Only limited region is shown to avoid overburden of the display routine.

Such an example is shown in Fig.5. Note that we killed the event generation because of too long computation time and too big file size (more than an hour and more than 10 GB trace file size for only a 10 MeV incident). The figure shows only limtted sector region with core distance > 3.4 km. This type of explosive events happens even at $\mathcal{E} = 240$ kV/m though the event rate is very small.

When the electron incident is 1 MeV (kinetic energy) with $\mathcal{E}$ =260 kV/m, big cascading (but not explosive) happens about half of events, for 500 keV $\sim 10\%$ and 300 keV $\sim 0.3\%$. The ingredient electron energy for the 300 keV case extends to more than 10 MeV (Fig.6). This means high energy bremsstrahlung photons make pair creation and positrons are also produced. However, the field is unfavored for positron energy gain and they stop soon.

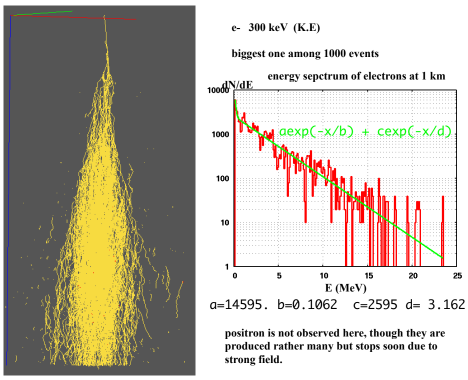


Figure 6: 300 keV electron generates a big cascade. Right fig: energy spectrum at 1 km

[2] It's still far from the dielectric breakdown of air ($\sim 3 \times 10^6$ kV/m) which we don't consider.

In view of these, the user is requested to control the $\mathcal{E}$ field region not only by the height but also by the lateral direction. For an impulsive field, time information may also be useful.

4.5 Effect on higher energy cascade

A 200 GeV electron primary is injected vertically at 7 km a.s.l. A uniform $\mathcal{E}$ up to 100 kV/m is applied below 5 km ($\mathcal{E}_c$ from Eq.2 at 5 km is $\sim$ 150 kV/m).

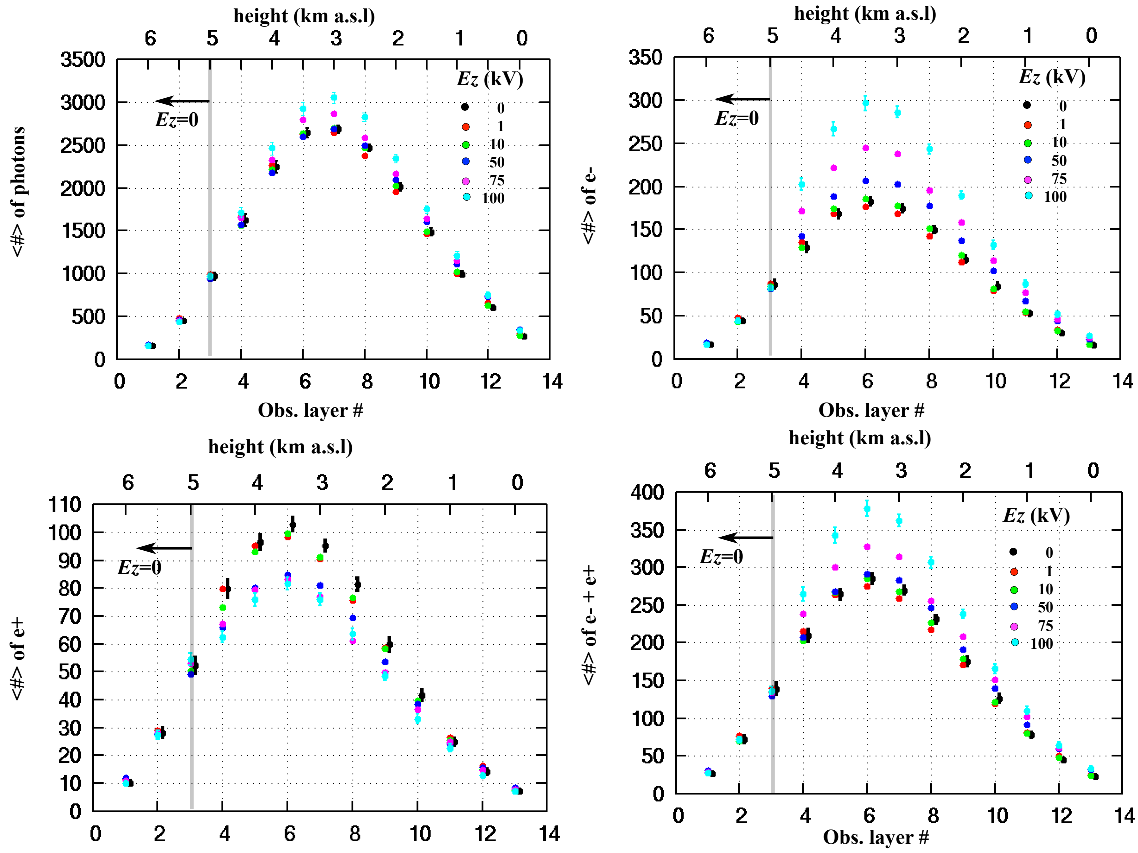


Figure 7: Average transtion curve for 50 showers of a 200 GeV electron incident. $\mathcal{E}_z = 0, 1, 10, 50, 75, 100$ kV/m. The case for 0 kV/m is shown after shifting the position a bit deeper place for visual convenance. The error bars for 0 and 100 kV/m cases are statistical ones. top left: photons, top right: e^-. bottom left: e^+, right: e^++e^-.

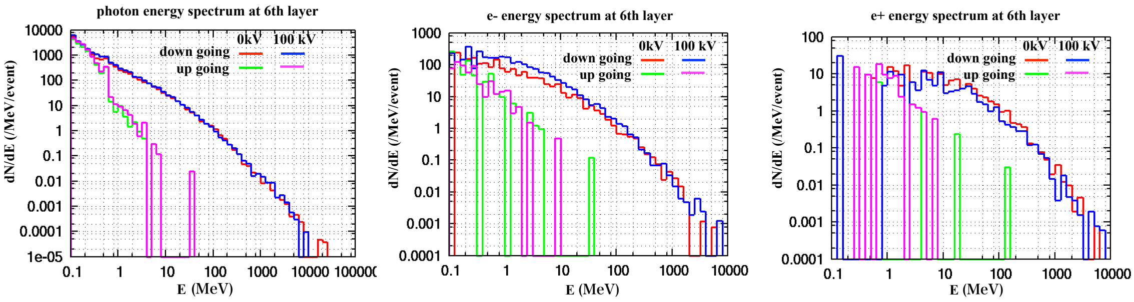


Figure 8: Average energy spectum/event at the 6th layer where the number of particles are largest. Left to right: photons, e^- and e^+. $\mathcal{E}_z = 0$ and 100 kV/m cases are compared. Structures at around photon energy of $E \sim 500$ keV are due to annihilation gamma rays. Down and up going particles are shown separately.

5 Template for an arbitrary electric field

A template file to generate an arbitrary electric field is included in `$COSMOSTOP/UserHook/cmyEfield.f`.
Preparation to use it is described in sec.3.

The code there is also not a realistic one. An electric field $\mathcal{E} = (0, 0, \mathcal{E}_z)$ with

$$\mathcal{E}_z = 360 \sin(\frac{\pi}{2}\frac{h}{2000}) \exp(-\frac{h}{5000}) \quad \text{kV/m} \tag{3}$$

is assumed (Fig.9). Here h is the height and this field is assumed only if $h < 7$ km and particle position satisfies $x > 0$ and $y > 0$. Otherwise, the field is 0.

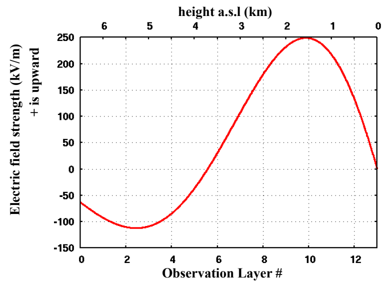


Figure 9: Assumed electric field

The origin to measure x, y is the origin of the deepest observation level, i.e,
(`call cxyz2det( ObsSites(NoOfSites).pos.xyz)...`).
The user can change the origin to another layer by changing "NoOfSites" to another value (in this example, there is no effect by such a change since the incident is vertical).

Except for the electric field, other conditions are the same as the previous one. Examples of shower image are shown in Fig.10

In the next Fig., the transition of the average number of particles are shown for photons and electrons. Abrupt change is observed at 1.5 km a.s.l where the $\mathcal{E}$ reaches max.

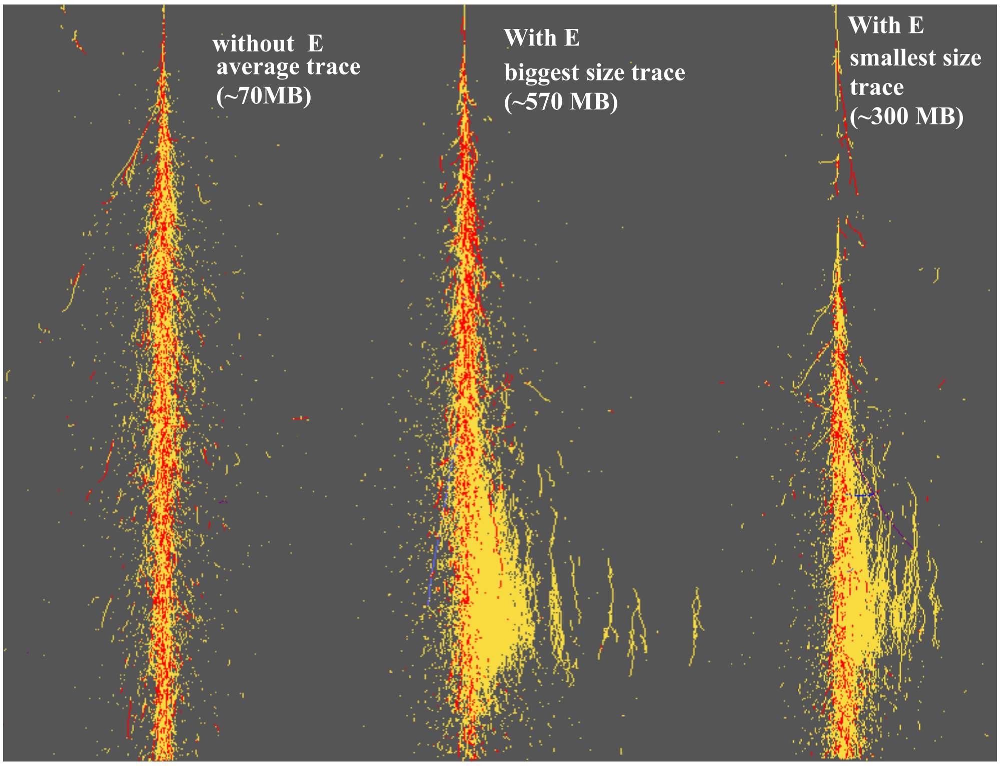


Figure 10: Shower trace examples. Left: no $\mathcal{E}$. Middle: biggest one example, and Right: smallest one example among 50 samples, when $\mathcal{E}$ exists. respectively. Increase of particles occurs only at $x, y > 0$ region.

6 Downwards Directed Field ($\mathcal{E}_z < 0$)

So far the field treated is $\mathcal{E}_z > 0$. If the field is directed downwards, electrons are decelerated, while positrons are accelerated so that, in the shower transtion curve, we will see the faster decrease of electron number and slower decrease of positron number than 0 field case.

In the case of $\mathcal{E}_z > 0$, Compton and knock-on electrons are the main source of increasing the number of electrons but for positrons, no such source is available and we may expect no big increase of positron numbers. This is true at low field strength, but with higher field strength, we see that electrons are pulled upwards and develop into an up going big cascade. Some of electrons and accelerated positrons can emit high energy bremsstrahlung photons which can produce e^+e^- pair. This leads to some degree of positron numbers increase.

In Fig.12 and 13, shower tracks are shown for various $\mathcal{E}_z$. Except for the direction of $\mathcal{E}_z$, conditions are the same as the previous case: A 200 GeV electron is injected vertically from 7 km a.s.l. A downwards directed vertical electric field exists below 5 km a.s.l.

The transition curves of photon, e^- and e^+ are shown in Fig.14, 15 for various $\mathcal{E}_z$

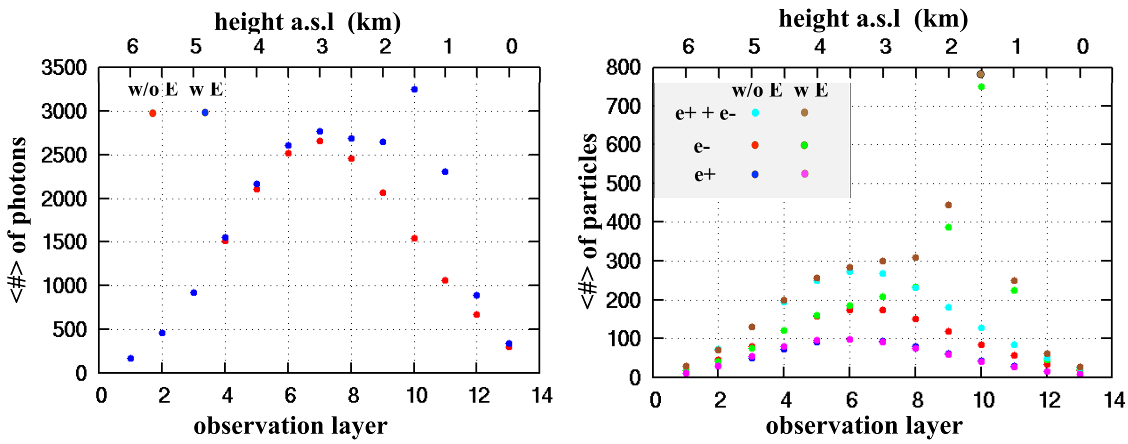
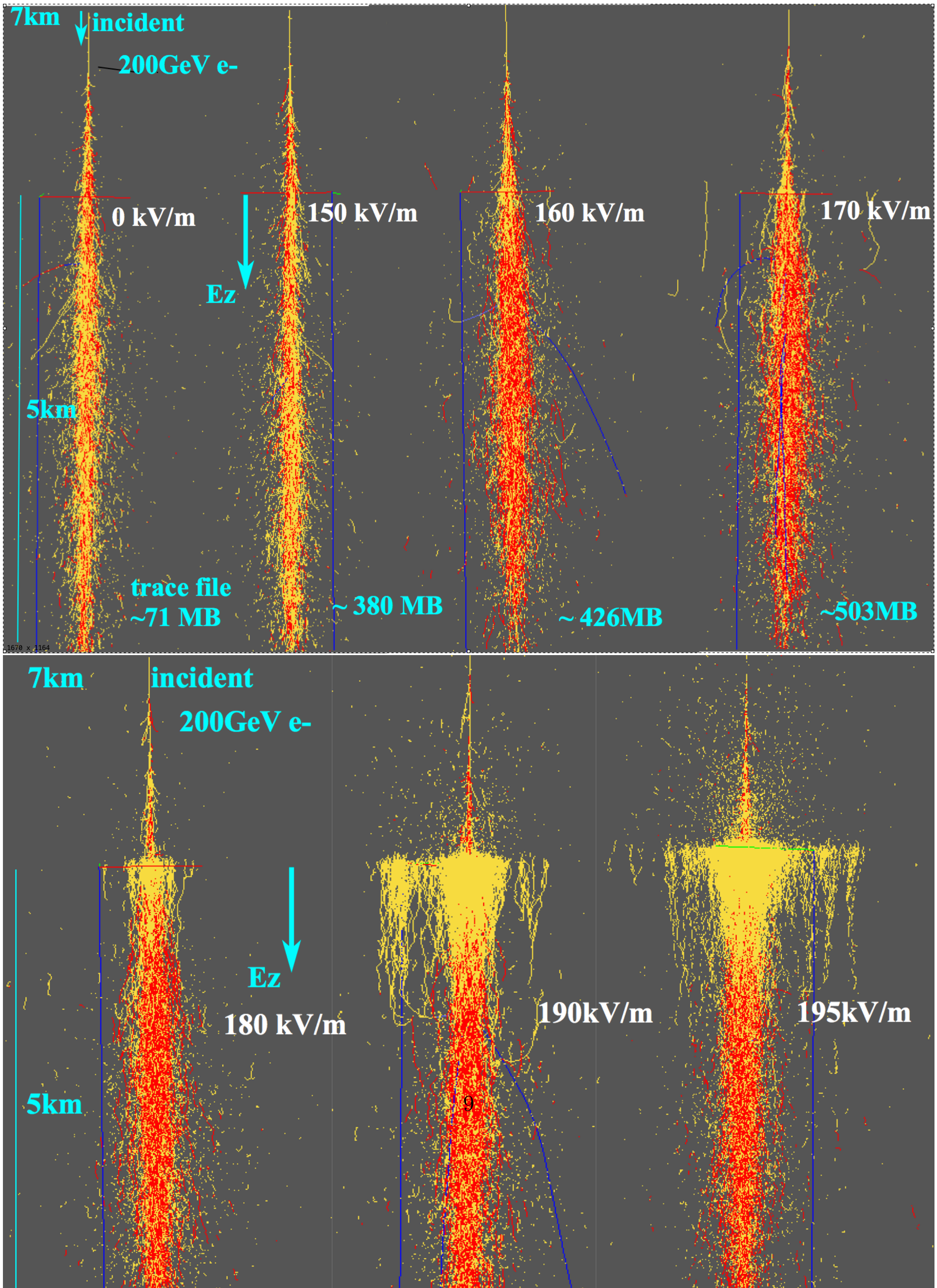


Figure 11: Average transition curve for photons (left) and electrons (right)



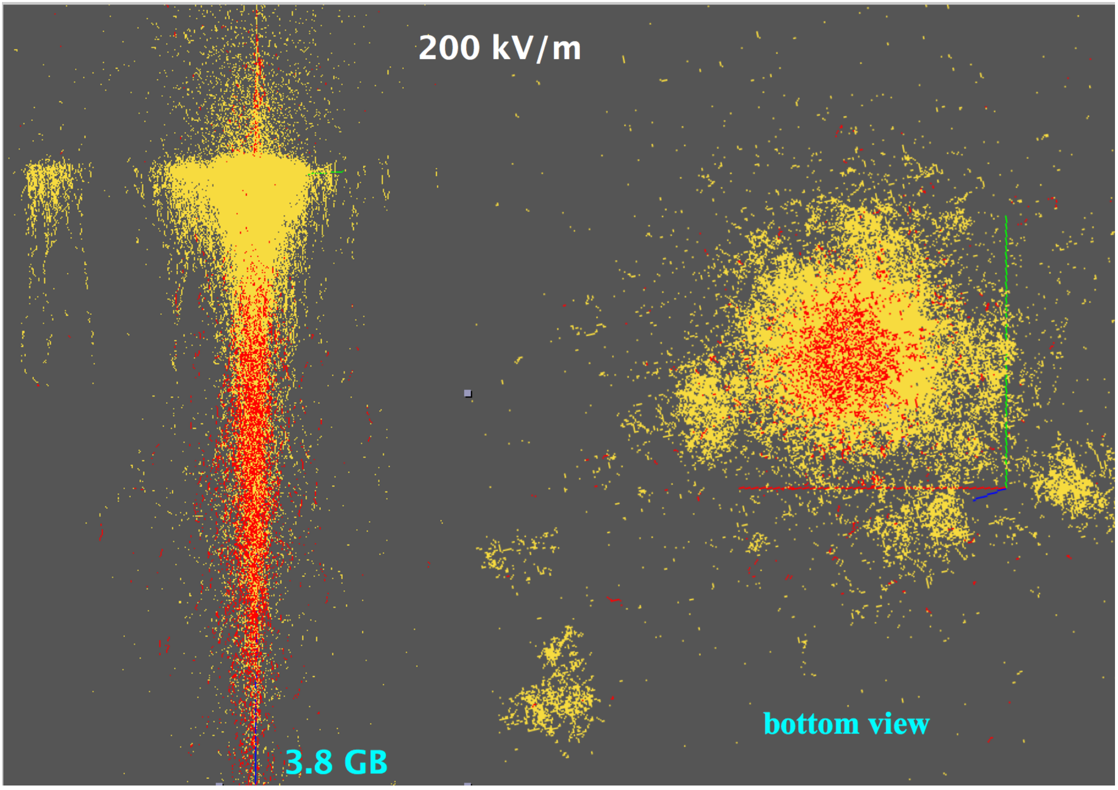


Figure 13: Cascade in downwards directed field. At around 200 kV/m field, explosive cascade may happen.

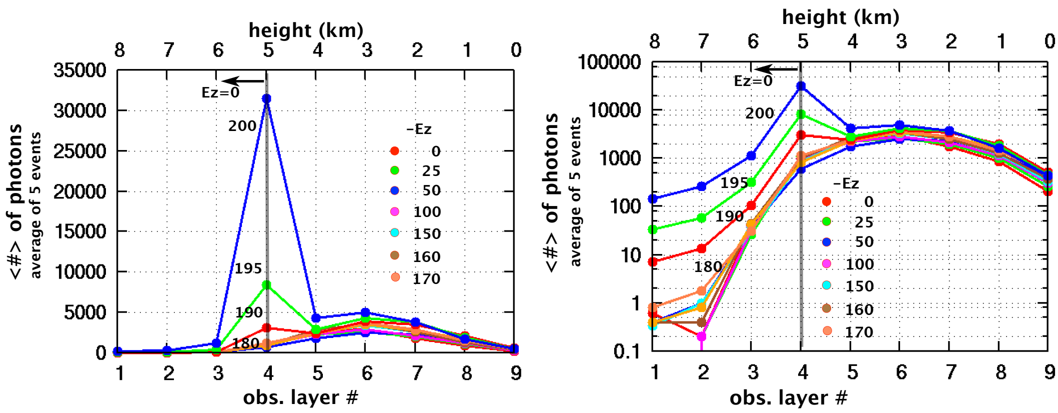


Figure 14: Transition curve of photons. Both up going and down going ones are counted. The lines are for easy tracking of the points. Left: in ordinary scale. Right: in log scale.

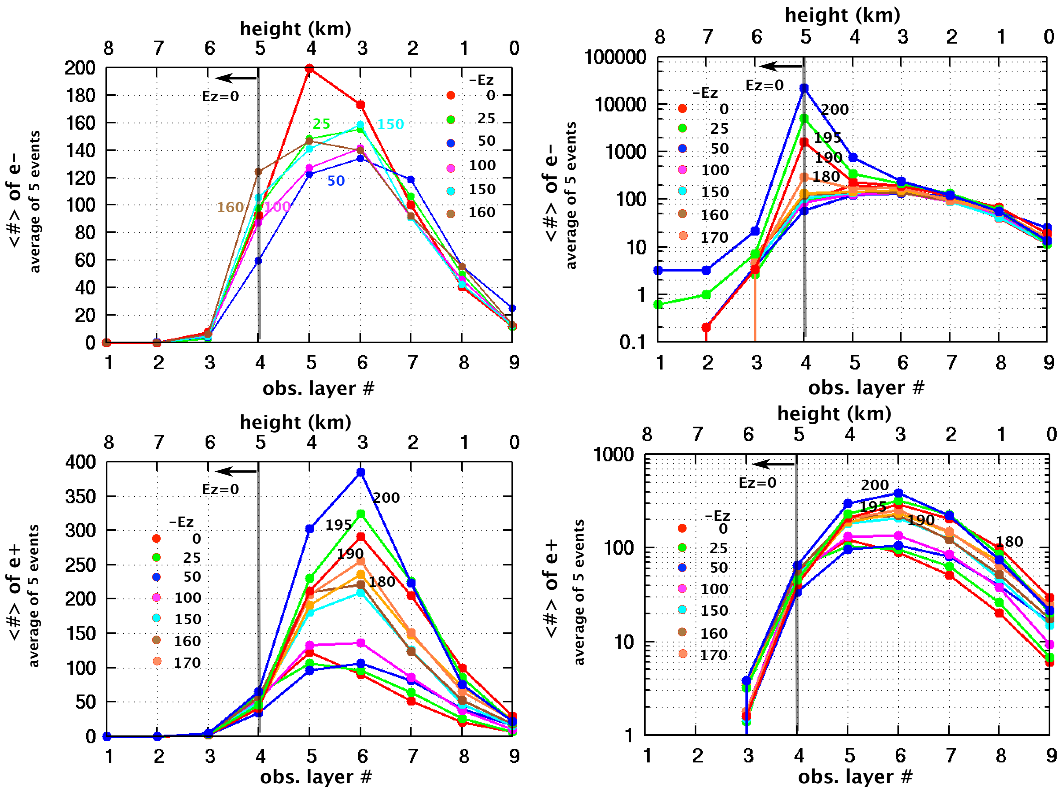


Figure 15: Transition curve of e^- and e^+. For e^-, high filed data is not shown in the ordinary scale figure.