Simulation of Positron Flux in Cascades of Runaway Electrons Generated by Cosmic Rays in Thunderstorm Atmosphere

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Abstract. Probabilities for positrons in cascades of runaway electrons produced by secondary cosmic rays in the strong electric field of underclouds to become runaway particles in the direction opposite to that of acceleration of electrons are calculated using modified GEANT4 code. Different electric field strengths and primary energies of electrons generating cascades are investigated.

1. Introduction
Galactic cosmic rays interacting with air atoms generate the permanent flux of many generations of secondary particles propagating deep into the atmosphere. This “equilibrium” flux is subject to variations associated with weather conditions (barometric and temperature effects). During thunderstorms the strong electric fields of thunderclouds form a very specific source of disturbance. The most abundant charged particles (electrons, positrons, and muons) are accelerated or decelerated depending on the field polarity and particle’s charge sign. Variations of secondary cosmic rays during thunderstorms were first proved to be related to the strong electric field (measured near the ground surface) in a pioneering experiment carried out by A.E. Chudakov with collaborators in early 1980s (for references see [1]). The new version of the same experiment [2, 3] yielded a lot of data on variations of cosmic rays during thunderstorms, and several other experiments are studying these phenomena too. The theory of electron runaway breakdown [4] seemed to be a natural basis for interpretation of experiments in this field. However, some peculiarities of enhancements of the soft component of cosmic rays (electrons, positrons, and gamma rays with energy 10-30 MeV) recorded in [2, 3] excluded simple explanation using this theory and required to suggest a new mechanism responsible for observed events. In order to explain experimental data, a mechanism of generation of elementary particles by thunderclouds was suggested in paper [5].

2. Feedback mechanism for avalanches of runaway electrons and problem of positrons
The essence of this mechanism is formation of a feedback loop in strong electric field: in one and the same field electrons are accelerated in one direction and positrons in the opposite direction. The process of pair production with subsequent Coulomb scattering turning back one component of the pair (moving against the accelerating field) closes the feedback loop. This positive feedback should lead to exponential growth of the particle density in a limited volume. It has been shown in [5] that energetically this process is definitely possible, the threshold field for this process exceeds the standard critical field of the theory of runaway electron breakdown only by 30%. Objections against this mechanism were made from the standpoint of probability of a single closed loop. This probability
heavily depends on the number of back-scattered positrons that can be produced in avalanches of runaway electrons. In this paper we simulate cascades of runaway electrons using a modified GEANT4 code and determine percentage of events with different numbers of positrons as a function of starting particle energy and field strength.

**Figure 1.** Cascades of particles generated by a single 1-MeV electron in the electric field with strength of 5 kV/cm. Electrons, positrons, and photons are represented by red, blue, and green lines, respectively. Starting point is at the center.

**Figure 2a.** Number of positrons (horizontal axis y) generated by electrons with energies up to 100 MeV (horizontal axis x) in the field 5 kV/cm.

**Figure 2b.** The same as in Fig. 1a for the field 4.5 kV/cm. Vertical axis represents probability as percentage of simulated events.
Figure 3. Lines of equal probability for generation of 1, 2, 5, and 10 positrons at different field strength and energy of a primary electron.

3. Simulation
The GEANT4 code (version 4.9.2) was modified (for details see [6]) to include electric field for simulation. An example of the simulated avalanche of particles produced in the 5 kV per cm electric field by a single electron with rather low energy of 1 MeV is demonstrated in Fig. 1. Here, the starting point of the initial electron moving downwards is located at the center of the picture. One can see that several cascades of electrons (red lines) are generated by gamma rays (green lines) at different places including those positioned higher than the starting point and far from the initial direction of motion (vertical). One can see also two positrons (blue lines) moving in the opposite direction. The aim of our simulation is to determine the mean number of up-going positrons generated in such cascades as a function of the electric field strength and energy of the primary particle. As many as 360000 cascades (3×10⁹ trajectories) generated by electrons with energies from 0.1 to 100 MeV were simulated in the field ranging from 2.25 to 5 kV/cm.
4. Results and discussion
Basic regularities of the positron flux behaviour can be seen in Figs. 2 and 3. At a fixed field strength the positron output is quasi-constant with energy in a wide energy range of 1 to 100 MeV. On the contrary, its dependence on the field strength is very strong. Of great interest is the fact that the number of positrons can be rather high (up to 10 positrons per a single initial electron). And this number is but a lower limit, since we take into account only newly generated positrons. At the same time in the equilibrium cosmic ray flux prior to its disturbance by the electric field always there are some number of scattered positrons and they start their motion and acceleration in the field immediately or after several acts of scattering. But even restricting ourselves to positrons produced in cascades of runaway electrons, we see that their mean number can be equal to four at 5 kV/cm field and 100 MeV generating particle (the flux of positrons exceeds the undisturbed flux of electrons four times!). Of course, 5 kV per cm is rather strong field, but the mean number of back-scattered positrons per one incident particle is still larger than unity at the field of order of 3.5 kV/cm.
It should be noted that feedback via positrons was discussed in literature previously, but in a bit different sense; J. Dwyer [7] calculated additional contribution to cascades of runaway electrons made by knock-on electrons produced by up-going positrons.

5. Acknowledgments
The work is supported by the Russian Foundation for Basic Research, grant no. 12-02-01028-a.

6. References
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