Research Networking Programmes

Short Visit Grant ☒ or Exchange Visit Grant ☐

(please tick the relevant box)

Scientific Report

The scientific report (WORD or PDF file – maximum of eight A4 pages) should be submitted online within one month of the event. It will be published on the ESF website.

***Proposal Title**:* The role of relativistic feedback in the production of TGFs by lightning leaders

Application Reference N°: 6927

1) Purpose of the visit

Following the work we started upon receiving the short-visit grant at the beginning of 2014, we will use both GEANT4 and in-house models to make an attempt at quantifying the role of relativistic feedback in the production of TGFs by lightning leaders.

2) Description of the work carried out during the visit

During the previous short visit at LPC2E (University of Orleans, CNRS) we made careful comparissons between the in house model of S. Celestin and the GEANT4 model of A. Skeltved. Progress was made to validate the GEANT4 programming toolkit to study the production of TGFs. This also contributed to a publication in Journal of Geophysical Research [Skeltved et al., 2014].

The work plan was conducted in the same way as previously. We scheduled a number of meetings to discuss and compare results. We had prepared calculations of the electric field in the vicinity of lightning leaders of different lengths, radii and ambient field strengths. We also agreed to perform some simple initial simulations in advance. During the first meeting we discussed the results we had prepared and then agreed on a set of milestones.

Two theories have been proposed to explain the production of high-energy photons in TGFs by bremsstrahlung from relativistic electrons: 1) The Runaway Relativistic Electron Avalanches and feedback theory and 2) The acceleration of electrons in streamer-leader electric fields.

In order to explain TGFs, electric potential drops in the vicinity of the lightning leader tip greater than ~100 MV have been inferred. In front of the leader tip, a magnitude of the electric field stronger than the RREA threshold can be present over distances on the order of one hundred meters. Under these conditions, relativistic feedback processes might have an impact on the number of photons produced. To our knowledge, the effects of relativistic feedback have never been quantified in the framework leader-producing TGFs theory.

Initial simulations of electron propagation in these strong inhomogeneous electric fields were then chosen to compare results from both models. A description of the two models can be found in Celestin and Pasko [2011] and GEANT4 collaboration [2012].

1- We have calculated the electric field in the vicinity of leader channels of different lengths, radii, and ambient electric fields using the method of moments [Balanis, 1989].

2- Along with initial conditions (65 keV electrons), we defined a small (5MV) and a large (300 MV) potential drop under which we simulated the developing electron population without taking the secondary electrons produced by bremsstrahlung photons and positrons into account. The former potential drop (5 MV) is believed to be typical for X-ray bursts from cloud-to-ground discharges [Xu et al., 2014] and the latter is representative of TGFs [Xu et al., 2012].

3- The same simulations was then performed with GEANT4 including the secondaries of bremsstrahlung photons and positrons.

4- We have formulated a preliminary conclusion on the role of relativistic feedback in the production of TGFs by lightning leaders.

3) Description of the main results obtained

1) The electic field in the vicinity of lightning leader tips are highly dynamic and can be very complex to calculate accurately. For this purpose we consider the simple case of a static situtation were the

leader is approximated by a perfect conducting cylinder immersed in a homogeneous electric field. Using the method of moments we can calculate the electric field ahead of the leader tip given the length, the cylinder radius, and the magnitude of the ambient homogeneous electric field. To get a 5 MV potential drop ahead of the negative leader tip, we choose a length of 1 km and an electric field of 0.1 kV/cm. For the case of 300 MV, we choose a leader length of 6 km and an electric field 1.0 kV/cm. The radii in both cases was set to be 1 cm. From Raizer and Bazelyan [2000, p. 68] the field at the leader tip sustaining streamer initiation is estimated to be 50 kV/cm. This is therefore set as the maximum field strength in the region very close to the tip. In addition, the initial thermal runaway electrons are assumed to have an energy of 65 keV and their initial position is given at the distance where the field drops below 50 kV/cm. That is 8 cm and 3 m for the 5 MV and 300 MV cases, respectively.

2) The main comparison, in order to verify that the modeling results are consistent, is on the electron energy distribution function (EEDF). In Figures 1 and 2, we show the EEDF at 3 ns and 30 ns for the 5 MV and 300 MV potential drops, respectively.

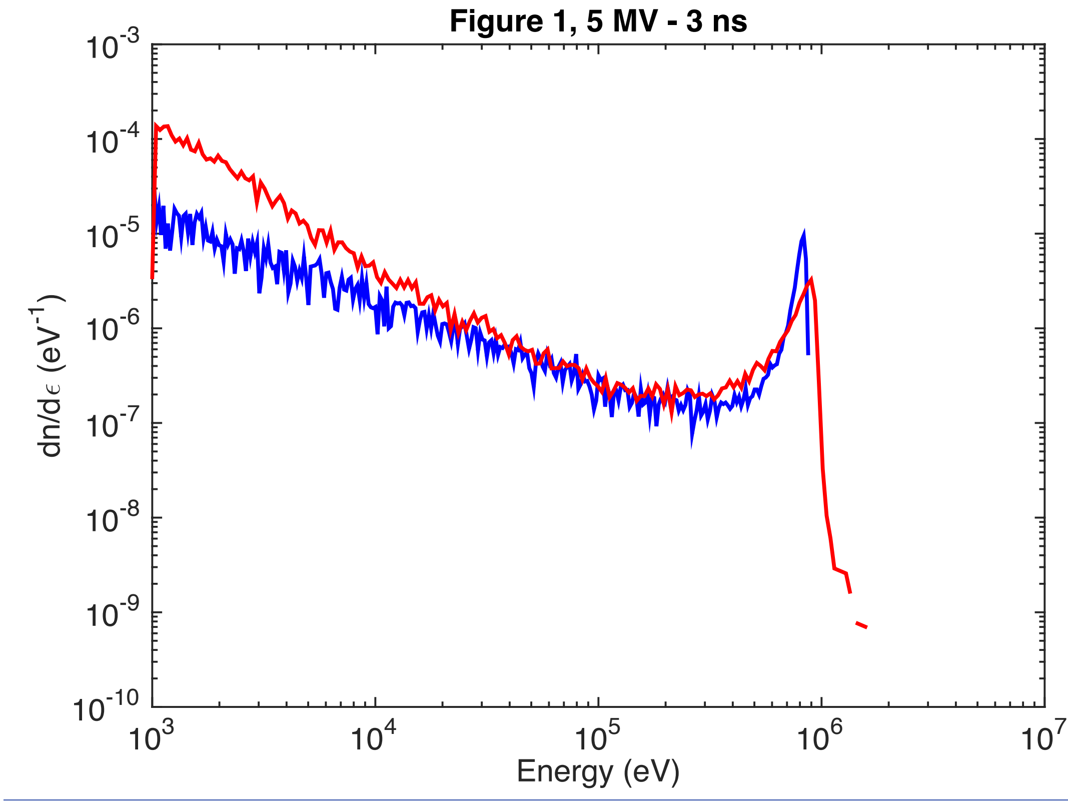

Figure 1: The EEDF calculated at t=3 ns in a potential drop of 5 MV. The curves are obtained from the model by S. Celestin (blue) and GEANT4

In both cases the results are in good agreement in the high energy region. However, some differences are to be noted at energies in the 10's to 100's of keV range.

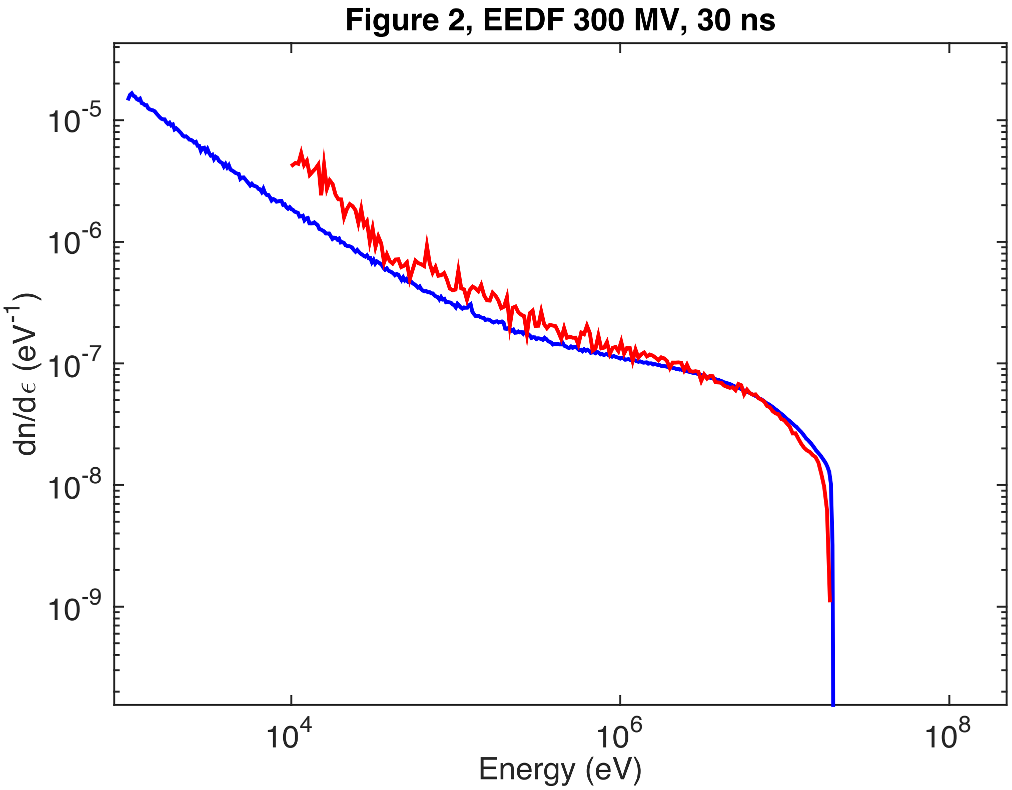

Figure 2: The EEDF calculated at t=30 ns in a potential drop of 300 MV. The blue curve shows the results obtained from S. Celestin's model and the red curve is the results obtained from GEANT4.

3) The effect of secondary electrons from bremsstrahlung photons and positrons is shown in Figure 3 (5 MV). In this figure we compare the number of secondary electrons (> 100 keV) with time from the two cases.

Figure 3 shows that high energy electrons correspond to seed electrons that have gained energy in the region close to the leader tip. Since the absoption length of photons capable of producing secondary electrons with energy >100 keV is larger than the acceleration region, the resulting secondary electrons will not contribute significantly until a much later stage. The contribution of the bremsstrahlung secondaries is seen as the red curve and becomes noticable at approxemately 0.035 microseconds, that is after the seed electrons have slowed down.

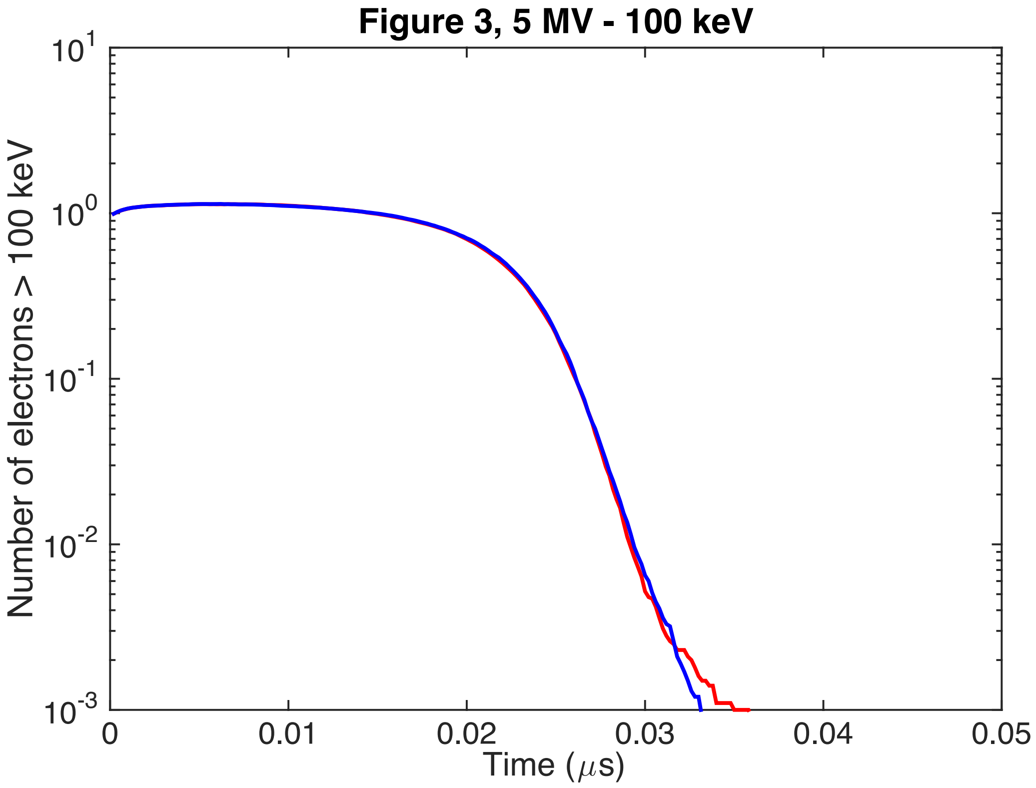

Figure 3: Number of electrons (>100keV) versus time, normalized to the number of initial electrons. The red curve includes secondary electrons produced by bremsstrahlung photons. The blue curve shows the electrons that are a part of the primary avalanche.

This general behavior is also observed in Figure 4 where we compare the number of electrons above 1 MeV for the 300 MV case. However, due to the significant number of high-energy photons in this case, a relatively high number of secondary electrons are produced ahead the high-field region produced by the leader. Precisely, these electrons are not feedback electrons as they are not able to further accelerate, but bremsstrahlung secondaries produced far from the leader. This is of importance as it might influence the TGF photon energy spectrum and fluence distributions.

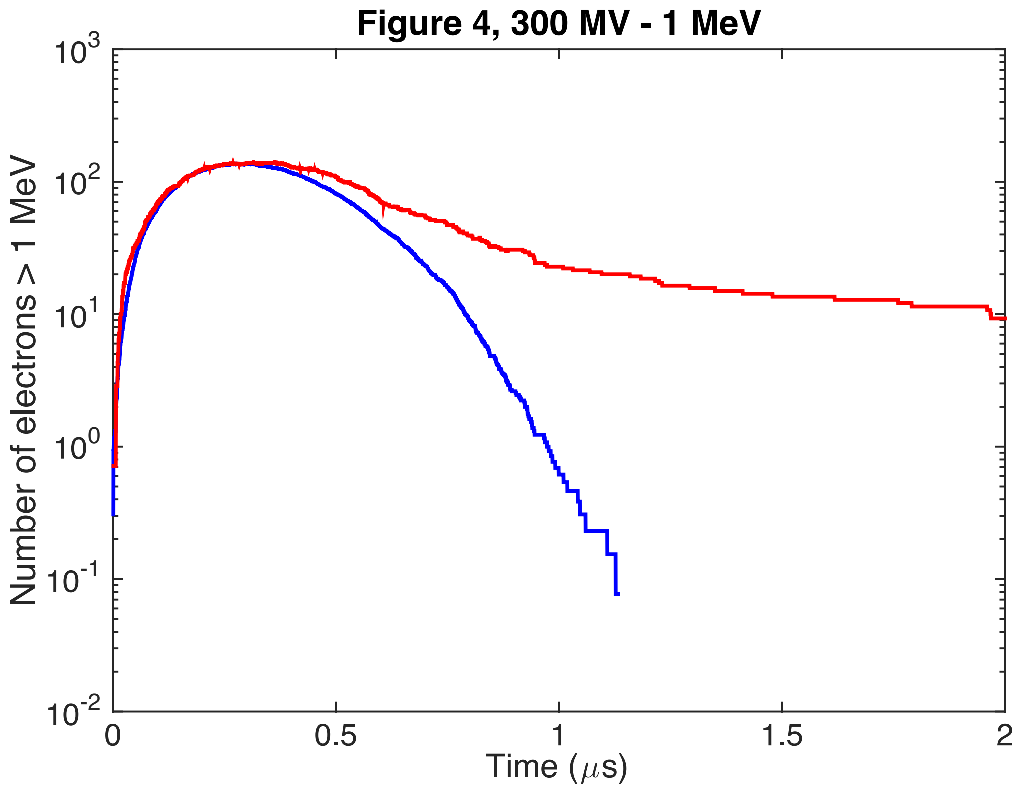

Figure 4: Number of electrons versus time (>1 MeV) in the 300 MV potential drop case normalized to the number of initial electrons including secondary electrons produced by bremsstrahlung photons (red) and those from the primary avalanche (blue).

From this we conclude that relativistic feedback in leader produced TGFs is not likely to play a significant role on the fluence of high energy photons. However, the effects of bremsstrahlung secondary electrons in the region ahead of the leader electric field, may be significant and has not been taken into account in previous work.

1) Future collaboration with host institution (if applicable)

This short-visit has given us the oppurtunity to explore new ideas on the nature of the production of TGFs. We have had the chance to expand on the results we obtained following the last short-visit and we have started new projects to continue the collaboration between our groups.

Much still remains to be explored. Some minor differences in our results remains to be resolved and related new ideas that have arisen during this visit will be investigated.

2) **Projected publications / articles resulting or to result from the grant *(ESF must be acknowledged in publications resulting from the grantee's work in relation with the grant)***

We are still in the preliminary stage of the development of the GEANT4-based modeling of leader producing TGFs, but following up on these ideas and through continued collaboration we intend to wrap this study up in a scientific paper when ready.

3) **Other comments (if any)**

References:

Skeltved, A. B., N. Østgaard, B. Carlson, T. Gjesteland, and S. Celestin (2014), Modeling the Relativistic Runaway Electron Avalanche and the feedback mechanism with GEANT4, *J. Geophys. Res.,* doi:10.1002/2014JA020504

Celestin, S., and V. P. Pasko, Energy and fluxes of thermal runaway electrons produced by exponential growth of streamers during the stepping of lightning leaders and in transient luminous events, Journal of Geophysical Research, 116, A03315, 2011.

GEANT4 collaboration, Physics Reference Manual version 10.0, (December), 2013.

Balanis, C. A., Advanced Engineering Electronmagnetics, 2. edition ed., 2012.

Xu, W., S. Celestin, and V. P. Pasko, Source altitudes of terrestrial gamma- ray flashes produced by lightning leaders, Geophysical Research Letters, 39(8), n/a–n/a, doi:10.1029/2012GL051351, 2012.

Xu,W., S. Celestin, and V. P. Pasko (2015), Optical emissions associated with terrestrial gamma ray flashes, J. Geophys. Res. Space Physics, 120, doi:10.1002/2014JA020425

Bazelyan, E. M., and Y. P. Raizer, Lightning Physics and Lightning Protection, 1.st ed., 68 pp., Nicki Dennis, New York, 2000.