Saturation of Relativistic-Runaway Electron Avalanches into Uniformly Propagating Ionization Fronts

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We study the fate of a Relativistic-Runaway Electron Avalanche (RREA) after it becomes intense enough that their constituent electrons interact with a non-negligible strength. Focusing on a planar-front case, we find that the RREA saturates into what we call a Relativistic Runaway Ionization Front (RRIF). This is a steady-state, uniformly propagating front with a long-tailed energy distribution.

1. Saturation of a RREA

Relativistic-runaway electron avalanches (RREAs) [1] are the keystone component of the nascent field of high-energy atmospheric physics [2]. A RREA consists of an exponentially growing number of relativistic electrons that, accelerated by an external electric field, have overcome the stopping power of their medium (generally air) and are able to ionize further molecules.

We implemented a Montecarlo (MC) model for a Relativistic-Runaway Electron Avalanche (RREA) with one spatial and three velocity dimensions. The MC code is coupled with the solution of the 1D electrostatic field.

We used this model to investigate the evolution of a RREA [3]. We found that when the electron density is large enough to screen the field behind, the exponential growth of the avalanche stops and the RREA saturates into an uniformly propagating ionization front that we name Relativistic Runaway Ionization Front (RRIF). This evolution is summarized in figure 1.

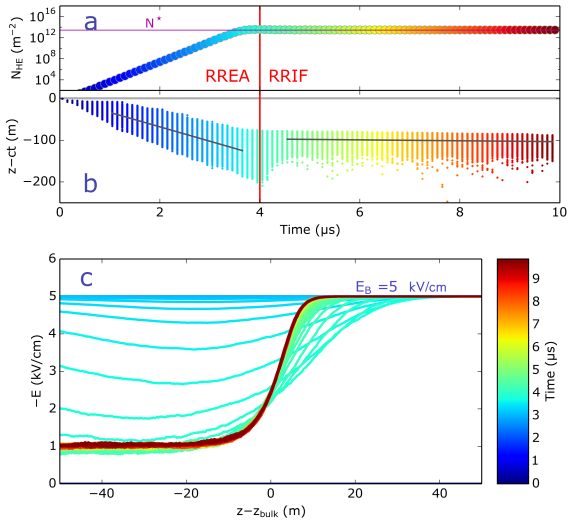

Fig. 1: Transition between a relativistic runaway electron avalanche (RREA) and a relativistic runaway ionization front (RRIF) under a background field $E_B = 5\,\mathrm{kV/cm}$. (a) After an phase of exponential growth, the number of high-energy electrons N_{HE} saturates when it screens the background field; the avalanche then transforms into a relativistic runaway ionization front (RRIF). (b) Location of high-energy electrons. We plot $z - ct$ in order to emphasize small deviations from a propagation at the speed of light c. The straight segments represent linear fits for the location of all particles as functions of time for the corresponding intervals. They correspond to velocities of $0.88c$ in the RREA regime and $0.996c$ in the RRIF regime. The propagating front (c) screens the upstream electric field, although not completely. The colors in (c) represent different snapshots in time, as indicated by the colorbar, and colors in panels (a) and (b).

2. Electron energy distribution

The electron energy distribution function of a RRIF is sharply different from that of a regular RREA. Figure 2 shows the resulting distribution functions for several driving electric fields. We also show there the distribution of photon energies emitted by the RRIF via electron-nucleus bremsstrahlung.

The most salient feature of figure 2 is the long tail of the electron distribution function, that approaches a power-law with exponent $\eta = -1$ up to a bremsstrahlung cutoff. This contrasts with the exponential cutoff at about 7.3 MeV in the RREA distribution function.

3. Analytical model of RRIFs

The distribution function discussed above can be

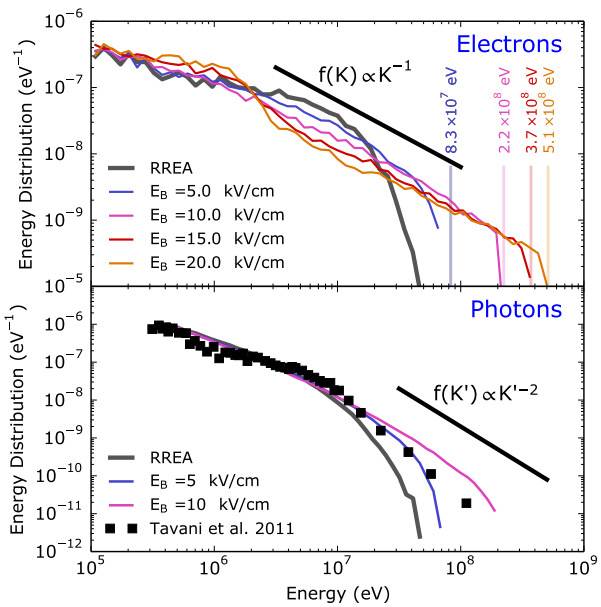

Fig. 2: Upper panel: distribution function $f(K)$ of RRIF electron energies K with different background electric fields E_B. The vertical bars indicate the bremmstrahlung cutoff energy. We also show the slope of a power-law spectra with exponent $\eta = -1$ and the spectrum of a RREA under a uniform background electric field $E_B = 5\,\mathrm{kV/cm}$; the RREA spectrum depends weakly on the driving electric field. Lower panel: distribution function $f(K')$ of energies K' of bremmstrahlung photons emmitted from a RREA and a RRIF and aggregate spectrum measured from AGILE [4].

explained by a relatively simple, analytical model of a RRIF. In this model, each high-energy electron is assumed to propagate forward until it undergoes an elastic scattering collision. One finds that the lifetime of electrons in the high-field region of the front is approximately proportional to their energy. This is the underlying reason for the power-law energy tail in figure 2.

This behaviour implies that electrons with higher energies receive proportionally more energy from the electric field. RRIFs can thus be seen as efficient particle accelerators. The power-law tail of a RRIF may also explain the observations by the AGILE satellite [4] of energies of up to about 100 MeV, deviating from the predictions of RREA models. An alternative explanation, in terms of strongly inhomogeneous electric fields close to a leader tip, was provided by Celestin *et al.* [5].

Acknowledgments: We acknowledge support from Spanish MINECO under project AYA2011-29936-C05-02 and by the Junta de Andalucia, Proyecto de Excelencia FQM-5965.

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