Observation of the Avalanche of Runaway Electrons in Air in a Strong Electric Field

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The generation of an avalanche of runaway electrons is demonstrated for the first time in a laboratory experiment. Two flows of runaway electrons are formed sequentially in an extended air discharge gap at the stage of delay of a pulsed breakdown. The first, picosecond, runaway electron flow is emitted in the cathode region where the field is enhanced. Being accelerated in the gap, this beam generates electrons due to impact ionization. These secondary electrons form a delayed avalanche of runaway electrons if the field is strong enough. The properties of the avalanche correspond to the existing notions about the runaway breakdown in air. The measured current of the avalanche exceeds up to an order the current of the initiating electron beam.

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The effect of electron runaway in a nonionized gas shows up in the presence of an electric field under both natural and laboratory conditions [1–5]. The most large-scale example is the phenomenon of runaway breakdown (RB) in a thunderstorm atmosphere [6–8]. The essence of the effect consists in the development of an avalanche of runaway electrons. For this to occur, fast initiating particles are required. In the limit of central collisions, the kinetic energy of an electron should be at least twice the runaway energy threshold ($\mathcal{E}_c$). In this case, the secondary electron can become a runaway electron also, and thus an avalanche is formed. The cascade ionization gives rise to a great many slow electrons, constituting a conducting medium in which breakdown occurs.

In a thunderstorm atmosphere at a normal conditions, RB is possible even in a field $E_c \approx 2.2$ kV/cm, which is much lower than the dc breakdown field ($E_{th} = 30$ kV/cm); however, the primary electron should have an energy exceeding hundreds of kiloelectronvolts [6–8]. The origin of such electrons is related to the passage of cosmic particles. According to estimates based on kinetic theory [7], the scale (avalanche size increment) over which the number of electrons in an RB avalanche in the atmosphere experience an exponential growth, l_a, is some tens of meters. Being accelerated on the interval l_a, the electrons gain relativistic energies of ~10 MeV and more. Therefore, an RB avalanche in a thunderstorm atmosphere is considered a "natural accelerator" and a source of intense bremsstrahlung flashes [9–15].

Direct evidence of the existence of the RB effect implies the detection of an avalanche of runaway electrons whose current is greater than the current of the initiating particles. The source of the fast initial electrons ($\mathcal{E} > 2\mathcal{E}_c$) and electric field exceeding some critical value should be provided in the discharge gap. If the field $E_c \approx 2.2$ kV/cm and $l_a \approx 50$ m [8], then the laboratory demonstration of RB becomes unrealistic because l_a is much greater than the width of the discharge gap (L) of the reasonable high-voltage facilities.

An RB avalanche can actually be observed in air in a strong field $E \gg E_c$ when the condition $L \geq l_a$ can be met in the laboratory setup. According to the RB similarity relations avalanche length $l_a(E) \propto \delta^{-2}$, avalanche growth time $\tau_a(E) \propto \delta^{-3/2}$and runaway threshold energy $\mathcal{E}_c(E) \propto \delta^{-1}$ where $\delta = E/E_c$ [16]. In a strong electric field $E \approx 10E_{th}$ or $\delta \approx 100$ the length $l_a(E) \approx 1$ cm, avalanche growth time $\tau_a \approx 100$ ps, and the runaway energy threshold $\mathcal{E}_c$ is only a few kiloelectronvolts. In accordance with these relations, we performed electric breakdown of air at atmospheric pressure in a gap of a few centimeters of length and in subnanosecond time scale.

Laboratory experiments necessarily involve the presence of electrodes. If $E > E_{th}$, the cathode inevitably becomes a source of field emission electrons initiating an ordinary pulsed breakdown (see, e.g., Refs. [5,17,18], and the cited works). Thus, an RB avalanche can be observed only at the stage of delay of pulsed breakdown. Under the conditions of multielectron initiation and $E \approx$ 200–300 kV/cm, this stage, which is understood as the period of existence of a field in the gap before the onset of conduction current, lasts several tens of picoseconds for air [18]. However, in view of the field rise time, the delay can become as long as a nanosecond, giving a chance of success if one uses a fast rise time high-voltage pulse [19]. In our experiment, the discharge gap [Fig. 1(a)] was formed by the tip of the central electrode and closed end face of the external conductor of a coaxial line. On the end face of the central electrode, a screen was placed which provided a field distribution, as shown in Fig. 1(b) by the dashed line.

A special problem is related to the generation of a picosecond initiating beam and its synchronization with the subnanosecond leading edge of the voltage pulse. Realizing that an electron accelerator cannot be disposed

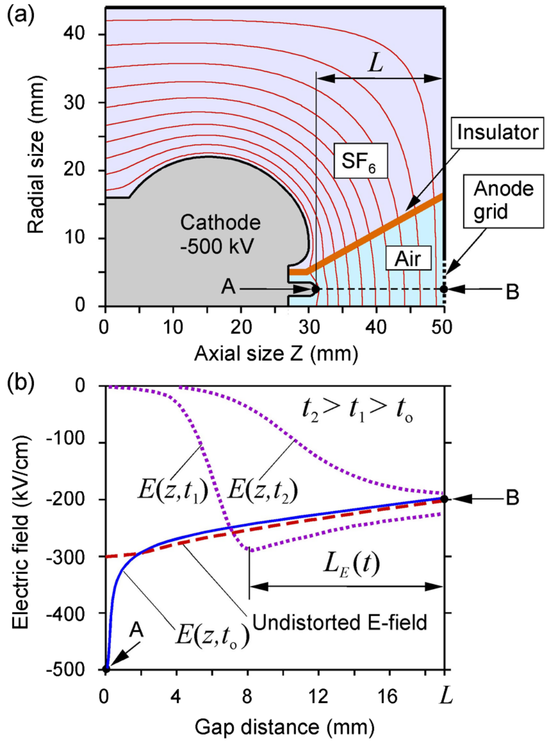

FIG. 1 (color online). Discharge gap with a tubular field enhancer. The equipotential map is shown (a). The electric field at the axis with no field enhancer (dashed line, calculation) and along the line *A*–*B* with an enhancer (a) at the time of onset of the beam emission, t_o (solid line, calculation). Phenomenology of the field variations with increasing gap conductivity due to propagation of ionization wave toward the anode (dotted lines) (b).

inside a high-voltage cathode of small diameter [see Fig. 1(a)], we abandoned the injection of an electron beam by an external source [20]. The matter is that a picosecond electron beam can be generated immediately in the discharge gap [21], and the problem of synchronization is solved automatically. To provide electron beam emission, the fact is harnessed that as the field is increased to the critical value of $E_o \approx 500$ kV/cm ($\delta > 150$), even the thermal electrons become runaway electrons in air [2–5]. The source of these particles, as in the case of pulsed breakdown, is the gas ionized in the cathode region. However, if E_o is achieved within a short time, which is less than the delay stage of an ordinary pulsed breakdown [5], another scenario could be realized where the beam of primary runaway electrons [runaway electron beam (REB)] is formed at once.

To do this, a microscopic irregularity (small protrusion or the like) is formed on the cathode. This provides a strong field enhancement in a local region near the enhancer, whereas the field in the gap varies unnoticeably [solid line in Fig. 1(b)]. The cathode screen is profiled so that the field at its surface would remain appreciably below E_o. In our experiments, the cathode no-load peak voltage reached -500 kV. Combined insulation was used to reduce the probability of the ordinary breakdown. The screen was insulated with SF_6 gas [see Fig. 1(a)]. As soon as the peak voltage is applied and the primary runaway electron beam is formed the fields drop below E_o rapidly due to gas ionization development near the enhancer [22]. That leads to REB termination. Numerical solution predicted that the REB duration can be as short as 20 ps [23]. The REB duration measured is generally not over 40–50 ps [21,24–26]. This has been demonstrated by means of an oscilloscope and a current probe whose transient responses were no worse than 30 ps [27]. The field enhancement factor can be changed by varying the geometry of the enhancer. Thus, it is possible to control (synchronize) the onset time of REB emission relative to the voltage pulse rise time.

According to measurements [21], the REB leading edge electrons are accelerated as moving in vacuum thus gaining the energy specified by the potential difference between the electrodes [28]. Outside the enhanced field region, the interaction of the REB with the gas is essentially similar to the case where the beam is injected by an accelerator. The beam is followed with an ionization wave [29]. The ionization cascades generate secondary electrons and as a strong field remains in the gap after the passage of the REB, the ionization wave will certainly contain electrons with energies $\geq \mathcal{E}_c$, which can initiate the RB avalanche.

After the passage of the REB, because of the rising conductivity of the gap, the residual field is "pushed out" toward the anode and decreases gradually. To moderate the field drop in our experiment, we used two approaches. The first approach consisted in some compensation of the field drop due to an increase in voltage after the termination of the REB emission. The second one was to reduce the REB charge, taking into account that the rate of the gap conductivity rise depends on the number of initiating electrons [5].

Figure 2 shows the part played by REB in the development of breakdown. Breakdown evidence can be obtained recording specific changes in the wave form of incident voltage pulse V_{in} after it is reflected from the gap (V_{ref}). If REB is not emitted, a breakdown is absent or delayed [20]. Completed breakdown leads to reversal of V_{ref} polarity [Figs. 2(c) and 2(d)]. The polarity reversal time is shorter by the factor 2–3 for the REB emission than for the case of breakdown without the beam. A proper choice of R_c and h [Fig. 2(b)] ensured the onset of REB emission at a time t_o at which the leading edge of V_{in} changed to a plateau. The width of the incident pulse V_{in} of 600–800 ps [Figs. 2(c) and 2(d)] is sufficient for the REB emission and acceleration as well as for development of successive breakdown in the gap. Breakdown maximal current was no less than 5 kA almost four orders higher than the REB current.

The waveforms given in Fig. 3 represent the electron current signals detected with no filter placed forward of the

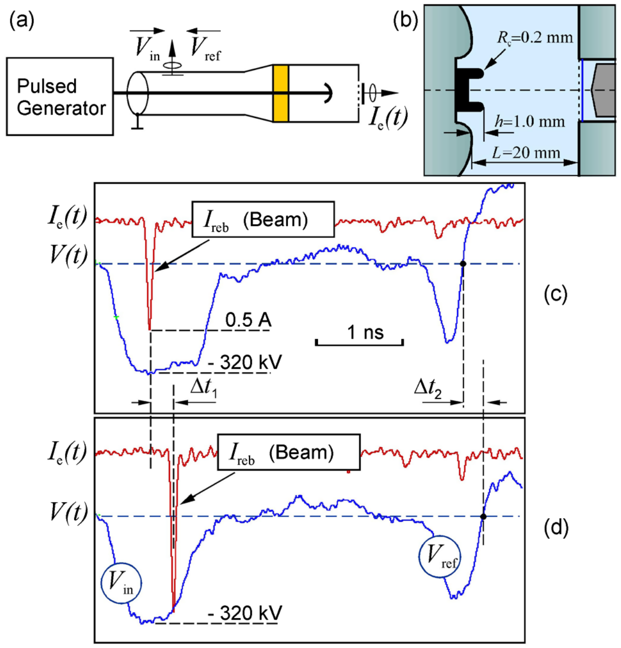

FIG. 2 (color online). Experimental arrangement (a). Geometry of the discharge gap with a tubular field enhancer (b). Waveforms of the incident (V_{in}) and reflected (V_{ref}) voltage pulses and of the electron current $I_e(t)$ at the collector screened with a grid and a 60 μm Al filter for different times of the onset of e-beam emission (c, d). For the time shifts of the REB emission and breakdown is valid $\Delta t_1 \approx \Delta t_2$ to within ~10 ps.

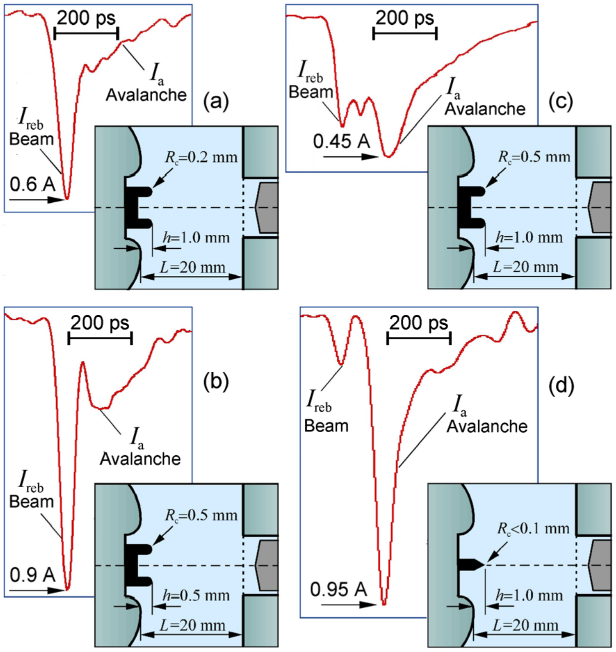

FIG. 3 (color online). Signals of the current from the electron collector taken with no absorber filter. The variations of the current amplitude ratio for the initiating beam and the delayed avalanche, (I_{reb}/I_a), on varying the geometry and axial position (h) of the cathode field enhancer are shown (a–d).

collector. A fine steel grid (30 μm wire, 50% transparency) was located in the anode plane to exclude detection of electromagnetic noise. Only electrons with energies above 6–7 keV could pass through the air gap between the grid and the collector (~ 1 mm) and arrive at the current probe. The waveform in Fig. 3, was recorded in the same mode as those in Figs. 2(c) and 2(d), but the absence of a filter had the result that the current I_a appeared after the passage of the pulsed beam current I_{reb}. Measurements have shown [20] that as the filter thickness was increased to 60 μm, the current I_a gradually ceased, and the energy ~90 keV can be considered an upper limit. The fivefold difference in electron energy between the I_a and the I_{reb} signal is rather substantial.

Figure 3(b) presents an amplification of the I_a signal and its discrimination with the REB in time when the field drop was delayed due to the voltage increase by 20% after the beam termination. With that, the REB electrons gained higher energies than in the case presented in Fig. 3(a). Figure 3(c) demonstrates a mode with the same V_{in} but when the beam was emitted ~150 ps earlier. This shift of the time t_o results in the onset of REB emission at a voltage lower by ~150 kV. However, after the REB emission, the voltage reaches the level as in Fig. 3(a) and continues to increase.

Figures 3(d) and 4 present application of a more radical measure, which had the result that the field drop was moderated for a reduced REB current. This was attained by decreasing the area of an emitter of initial thermal electrons. Cathode field enhancers were used which had the shape of thin rods with a pointed or a rounded edge. A significant decrease in REB current [see Figs. 3(d) and 4] and advanced beam emission [even earlier as compared to the regime shown at Fig. 3(c)] resulted in an evident increase in avalanche current. For the case with a rounded field enhancer, the electron current was analyzed by varying the cutoff energy W_{cut} with a set of filters (see Fig. 4). It can be seen that the main contribution to the avalanche

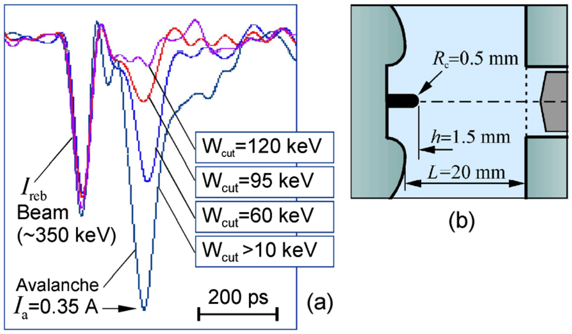

FIG. 4 (color online). Signals of the current from the electron collector taken with absorber filters with a varied cutoff energy W_{cut} (a). Geometry of the cathode field enhancer shaped as a rod with a rounded edge (b).

signal was made by the particles with energies less than 60 keV. The electrons with the highest energy (~ 120 keV) moved nearer the REB, whose energy reached 350 keV. From the classical Bethe formula [30] it follows that at normal atmospheric conditions for the energies of electrons 6, 60, and 90 keV, friction force will be 78, 14, and 9 keV/cm, respectively. In our experiments, strong electric field determines accelerating force exceeding $eE \sim 200$ keV/cm. As this force is much higher than the friction force, electrons of secondary avalanche recorded at $\mathcal{E} > 6$ keV (Figs. 3 and 4) are runaway electrons, by definition.

Finally, we note that the I_a and I_{reb} signals yield the lower estimate of the ratio for the currents of the avalanche and the beam. In the experiment, a paraxial small-area collector ensured picosecond resolution. A high-energy REB is better oriented along the field, and the distribution function of the comparatively slower secondary electrons is more isotropic in angle. Therefore, it is not improbable that the integrated avalanche signal I_a could be more intense than I_{reb} even for the modes presented in Figs. 3(a) and 3(b). For the case shown in Fig. 3(d), the difference in intensity between these signals was, undoubtedly, much more than tenfold.

The results obtained can be summarized as follows: Breakdown of an air gap in a strong electric field ($E \approx 10E_{th}$) was realized after the passage of a short beam of high-energy electrons. Behind the beam, a time-discriminated electron flow arose that built up in an avalanchelike manner. The energy of registered electrons in the flow was higher then 6 keV, it was far below the energy of the beam, and had a pronounced upper limit about 100 keV.

A current (charge) for the avalanche signal much greater than that for the beam was attained. The avalanche growth time was of the order of 10^2 ps. The observed avalanche of runaway electrons was entirely the same in nature as that inherent in runaway electron breakdown of air in the presence of a strong nonsteady field.

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