Formation of the Secondary Runaway Electron Flow in an Elongated Atmospheric Gap

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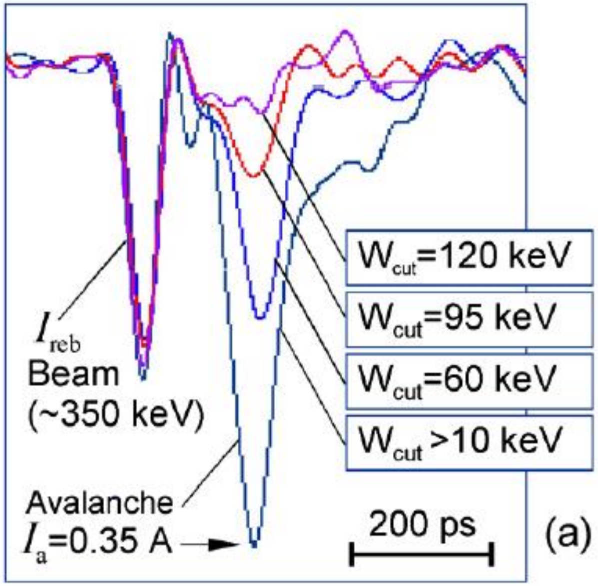
1. Motivation

In the experiments reported in Refs. [1,2], when a negative high-voltage pulse with a subnanosecond leading edge is applied to the cathode of the atmospheric pressure air gap with a sharply inhomogeneous electric field *E*, doublets of picosecond current peaks of high-energy electrons are recorded: a secondary fast electron flow is generated that is delayed relative to the primary picosecond flow of runaway electrons (REs). Similar effects were observed in the experiments [3] and numerical simulations [4].



[1] A.V. Gurevich, G.A. Mesyats, K.P. Zybin A.G. Reutova, V.G. Shpak, S.A. Shunailov, and M.I. Yalandin, Phys. Lett. A, **375**, 2845 (2011).

[2] A.V. Gurevich, G.A. Mesyats, K.P. Zybin, M.I. Yalandin, A.G. Reutova, V.G. Shpak, and S.A. Shunailov, Phys. Rev. Lett. 109, 085002 (2012).

[3] V.F. Tarasenko, D.A. Sorokin, M.I. Lomaev, Tech. Phys. **61**, 1551 (2016).

[4] A.V. Kozyrev, E.M. Baranova, V.Yu. Kozhevnikov, and N.S. Semenyuk, Tech. Phys. Lett. **43**, 804 (2017).

2. Motivation

The nature of the first current peak is not in doubt. These are REs [5,6] emitted from the plasma boundary near the cathode, where the electric field strength can be much higher than a critical value ~450 kV/cm due to distortion by a *E*-field enhancer. Sufficiently high energy of the secondary particles qualifies them also as REs. Nevertheless, the mechanism of generation of secondary RE flow (REF2) is still not entirely clear: see, e.g., [7].

In the present work, we analyze features of the burst of fast electrons arriving to the anode of elongated, air-filled gap with a sharply inhomogeneous electric field with a delay relative to the primary picosecond RE flow (REF1). The secondary flow appearance suggests impact ionization of the gas in the main part of the gap by REF1, as well as the presence of a residual electric field and its dynamic transformation due to propagation of the ionization wave toward the anode. Considering this concept, it is possible to explain the sensitivity of the delay between REF1 and REF2 to the cathode-anode distance and to the regime of the ionization wave cut-off by an additional, floating-potential Al foil electrode partially transparent for primary REs. The use of an ionization agent in the form of bremsstrahlung from a similar, Ta foil electrode opaque to primary REs leads to an earlier arrival of REF2 to the anode.

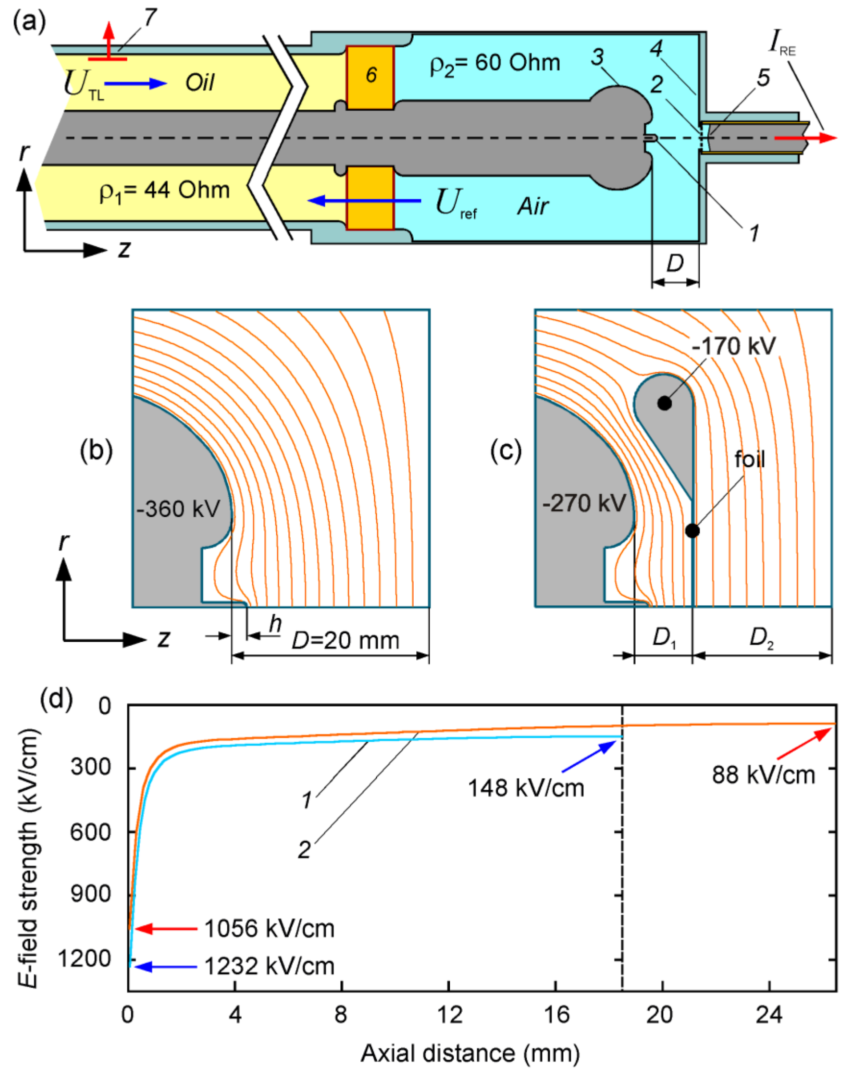
[5] H. Dreicer, I, Phys. Rev. **115**, 238–249 (1959).

[6] A.V. Gurevich, J. Exp. Theor. Phys. **12**, 904–912 (1961).

[7] I.M. Kutsyk, L.P. Babich, E.N. Donskoi, E.I. Bochkov, JETP Lett. **95**, 631-636 (2012).

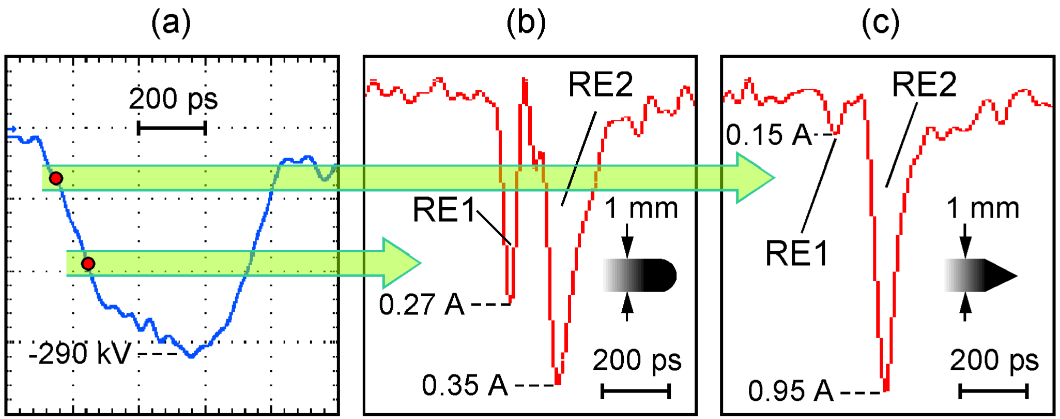
Experimental setup

The pulse U_{TL} of a subnanosecond high-voltage generator based on the nanosecond driver RADAN-303 and inductive-capacitive pulse compression unit was supplied to the gas section via a transmission line (TL) ending with a gradient screen and a cathode field enhancer.



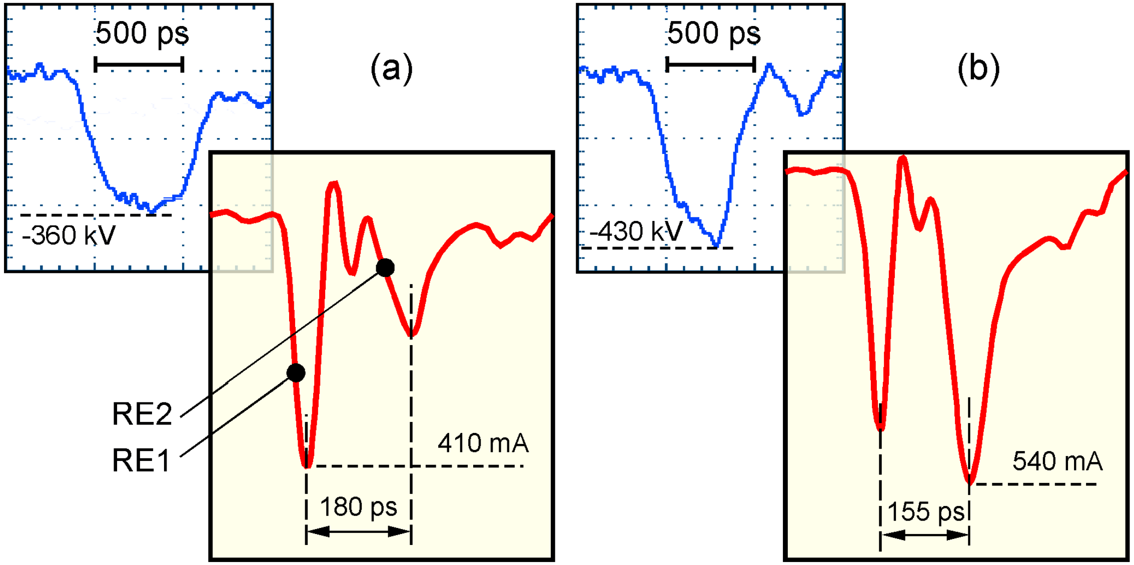
<u>Figure</u>: (a) Design of the high-voltage unit of the experimental setup: 1 - field enhancer, 2 - anode grid (foil), 3 - gradient screen, 4 - anode, 5 - electron current collector, 6 - insulator, and 7 - capacitive voltage sensor. (b, c) Configurations of two- and three-electrode gap; equipotential surfaces are also shown. (d) Field distribution on the axis of two-electrode gaps with the cathode potential of -360 kV on the interval (D - h) starting from the edge $z = 0$ of the E-field enhancer with h = 1.5 mm for the gaps of D = 20 and 28 mm width (curves 1, 2).

1. Experimental results



<u>Figure:</u> Travelling voltage pulse applied to the cathode (a) and the current doublets of REs emitted at different points of the voltage front for round-edge (b) and sharp-edge (c) *E*-field enhancers.

<u>Figure:</u> Transformation of the delay between RE1 and RE2 flows for an unchanged position of the round-edge *E*-field enhancer, when only the voltage amplitude (presented in idle mode) and the steepness of its front are varied.



2. Experimental results

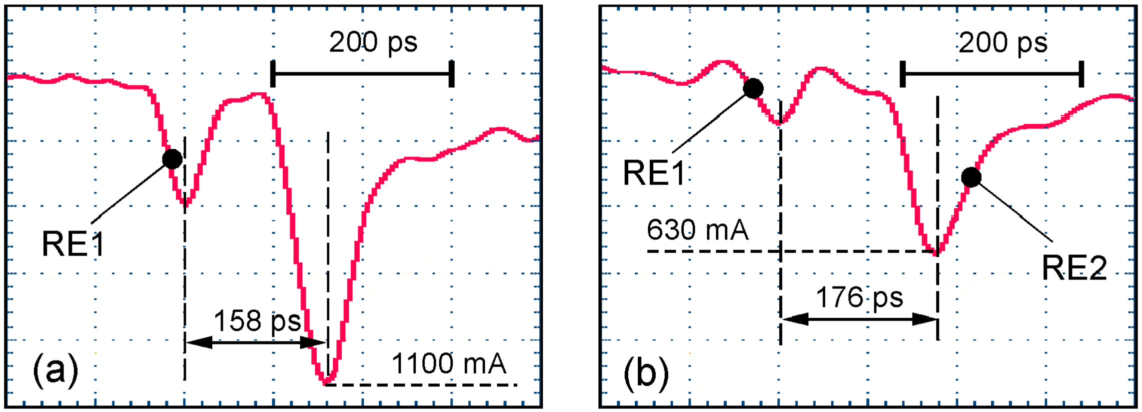


Figure: Delay between REF1 and REF2 for the case of the gap distance (D - h) variation from 18 (a) to 26 mm (b). Geometry and position of E-field enhancer are unchanged.

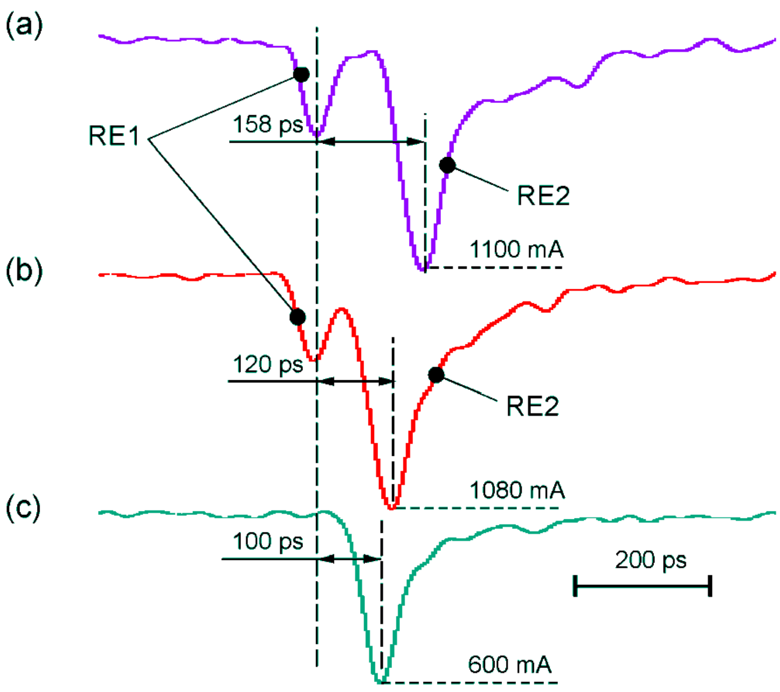
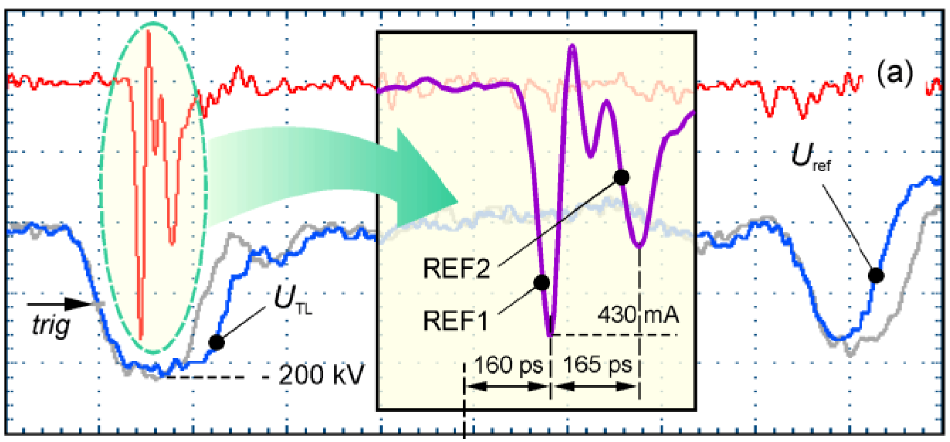
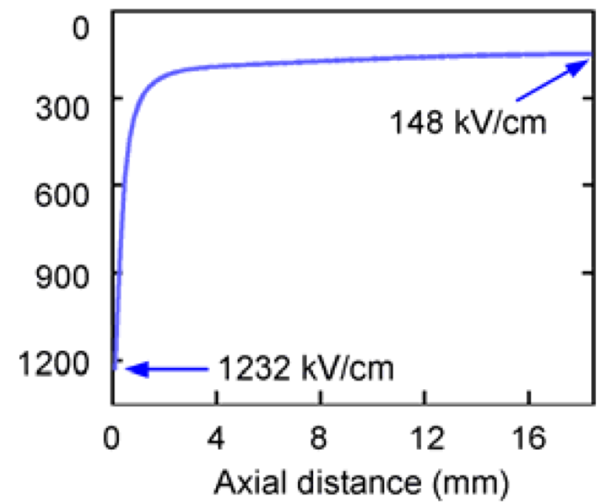


Figure: Delay between REF1 and REF2 for a two-electrode gap with the width $D - h$ = 18 mm (a) and for the case of the same gap with intermediate floating-potential Al-foil electrode placed at the distance $D_1 - h = 4$ mm from the cathode (b). (c) Earlier arrival of secondary REs at the anode in the case when tantalum foil was used as an intermediate electrode, which produces bremsstrahlung under the action of REF1.

1. Interpretation and discussion

The main question that arises when considering the obtained experimental results concerns the interpretation of the formation of separate current peaks corresponding to REF1 and REF2.

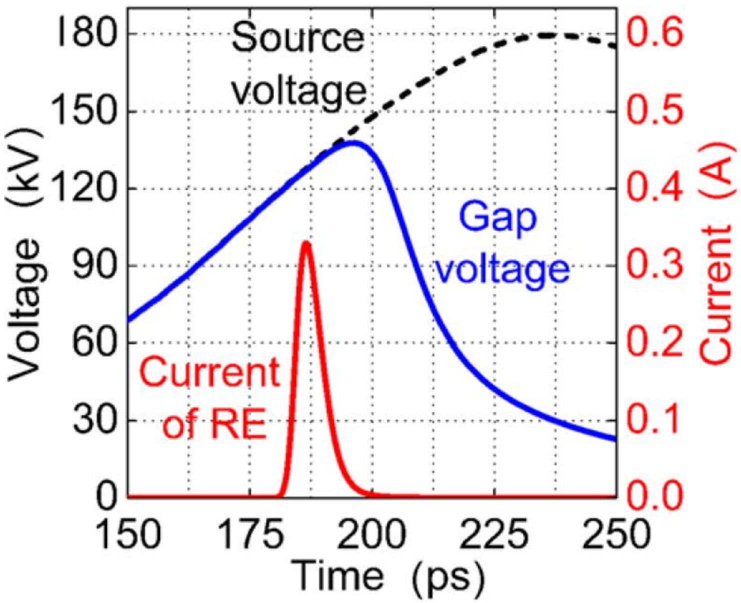




Let us consider the experiment where both primary and secondary REs cross the gap at the plateau of the voltage pulse, i.e., at its amplitude (in idle mode) value U_c = - 360 kV. If, for simplicity, we set the field distribution in the main part of the gap to be uniform, this case will correspond to the absolute value of the field strength $E = |U_c|/D \approx 180$ kV/cm (here we ignore the submillimeter region with a sharply inhomogeneous field in the vicinity of the cathode).

2. Interpretation and discussion

For the duration of REF1, the problem was analyzed in detail in our recent paper [8]. For simplicity, we assume here that REF1 has a negligible duration: its time profile can be approximated by the Dirac delta function.



Three basic scenarios can be distinguished for separating the total REF into two flows, REF1 and REF2. The reason for the “grouping” of REF2 at the anode can be explained by the features of the dynamics of the secondary REs “sown” by the primary REs along the interelectrode gap.

[8] G.A. Mesyats, M.I. Yalandin, N.M. Zubarev, A.G. Sadykova, K.A. Sharypov, V.G. Shpak, S.A. Shunailov, M.R. Ulmaskulov, O.V. Zubareva, A.V. Kozyrev, and N. S. Semeniuk, Appl. Phys. Lett. **116**, 063501 (2020).

Scenario I

The first possible scenario is based on the assumption that while REF1 moves in an unperturbed electric field *E* ahead of the ionization wave, REF2 lags behind the wave front, and hence, propagates in a weaker field $E_l < E$.

$$T = \frac{D}{c}\sqrt{1+\frac{2\varepsilon_0}{eED}}$$

$$\varepsilon_0 = m_e c^2 \approx 511\ \text{keV}$$

$$T(E_l) - T(E) \approx 165\ \text{ps}$$

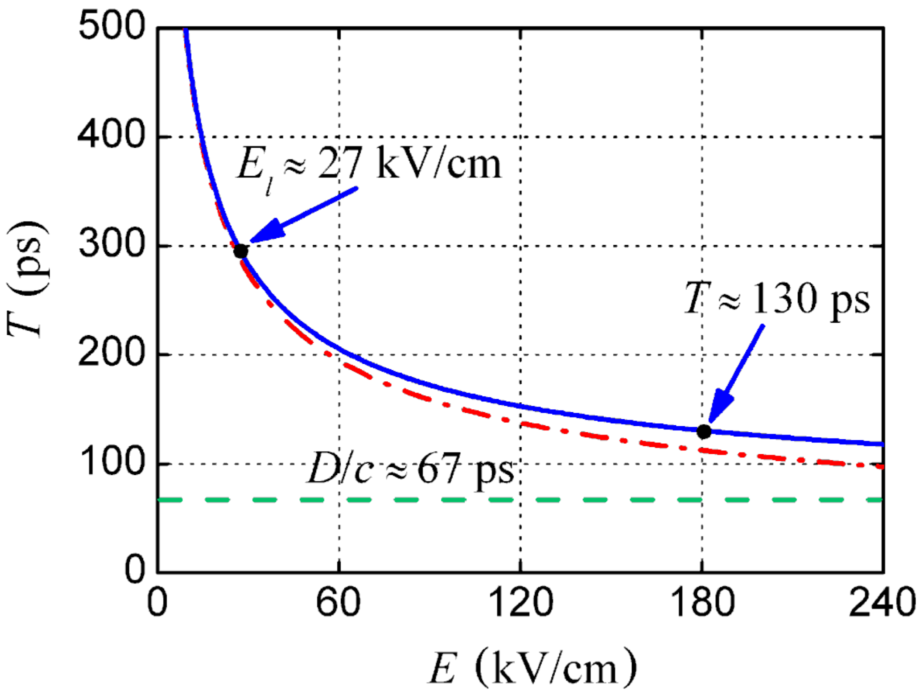


Figure: Dependence of the time-of-flight *T* of REs through the 2 cm gap on the electric field strength *E*. The solid line corresponds to the relativistic estimate, the dash-dotted line to the nonrelativistic one. The horizontal dashed line gives the light crossing time (67 ps) through the gap.

Scenario II

The second scenario is based on the fact that most secondary REs are created with minimum energy sufficient for their subsequent runaway. Then the initial velocity of secondary REs is lower than that of the primary REs. This circumstance will lead to their lag even under conditions of a constant electric field in the inter-electrode gap.

The secondary REs generated at some point z will arrive at the anode at the moment t_a given by

$$t_a(z) = \frac{z}{c}\sqrt{1+\frac{2\varepsilon_0}{eEz}} + \frac{D-z}{c}\sqrt{1+\frac{2\varepsilon_0}{eE_l(D-z)}}.$$

Here, the first term corresponds to the moment of passage of REF1 through the point z, and the second term corresponds to the time-of-flight of secondary REs between this point and the anode.

Scenario II

It is important that Scenario II is able not only to provide an extended tail of secondary REs lagging behind the primary ones, like in Scenario I, but also a separate peak of the RE current at the anode.

The secondary REs created in the spatial interval $0 < z < 1$ cm reach the anode practically simultaneously (within ~20 ps).

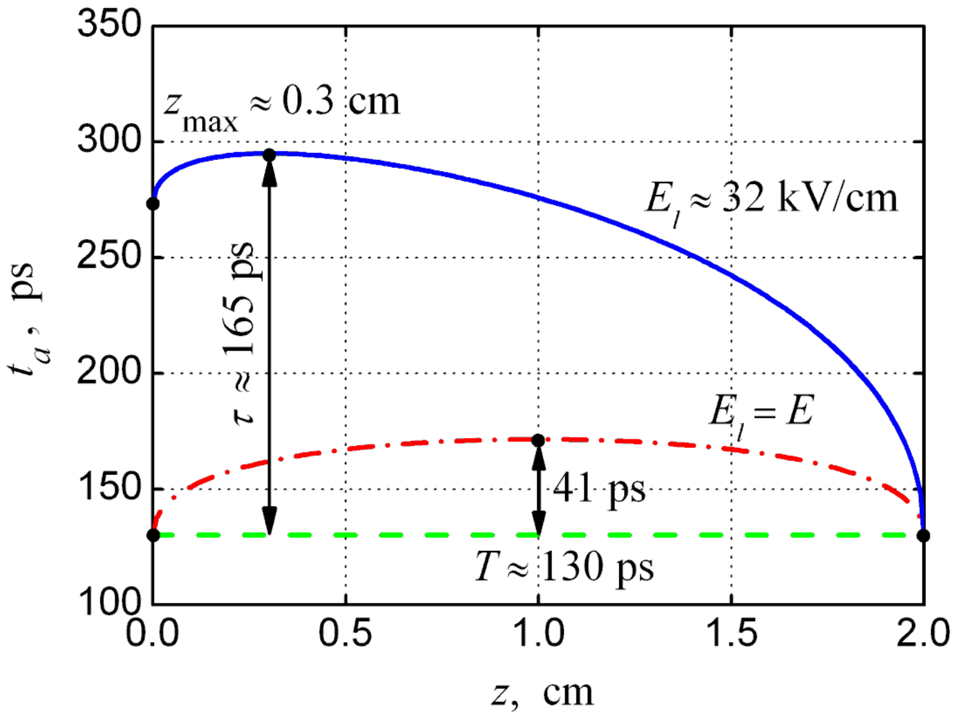


Figure: Dependence of the moment t_a when secondary REs fall onto the anode on the coordinate of their creation z for $D = 2$ cm and $E = 180$ kV/cm (the time is counted from the start of REF1 from the near-cathode region). The solid and dash-dotted lines correspond to $E_l = 0.18\ E$ and $E_l = E$, respectively; the dashed line indicates the moment when REF1 particles reach the anode.

Scenario III

The third possible scenario for delaying REF2 relative to REF1 takes into account that secondary REs are not necessarily originated directly as a result of impact ionization of gas molecules by REF1 particles. These fast electrons may be originated indirectly. Initially, thermal electrons are generated, then avalanche multiplication of these low-energetic electrons occurs, and only later some fraction of them goes into the runaway mode in an enhanced electric field at the front of the ionization wave. The ionization wave initiated by REF1 propagates from the cathode to the anode with increasing velocity. For estimates, we will assume that the wave lags behind REF1 in *s* times. As a result, we get the following estimate for the time when secondary REs created at the point *z* reach the anode:

$$t_a(z) = \frac{sz}{c}\sqrt{1+\frac{2\varepsilon_0}{eEz}} + \frac{D-z}{c}\sqrt{1+\frac{2\varepsilon_0}{eE(D-z)}}$$

The experimentally observed delay of ~165 ps between REF1 and REF2 is realized for $s \approx 2.1$

Scenario III

Secondary REs created in a wide region $1.1 < z < 2$ cm reach the anode within a relatively short time frame of ~20 ps.

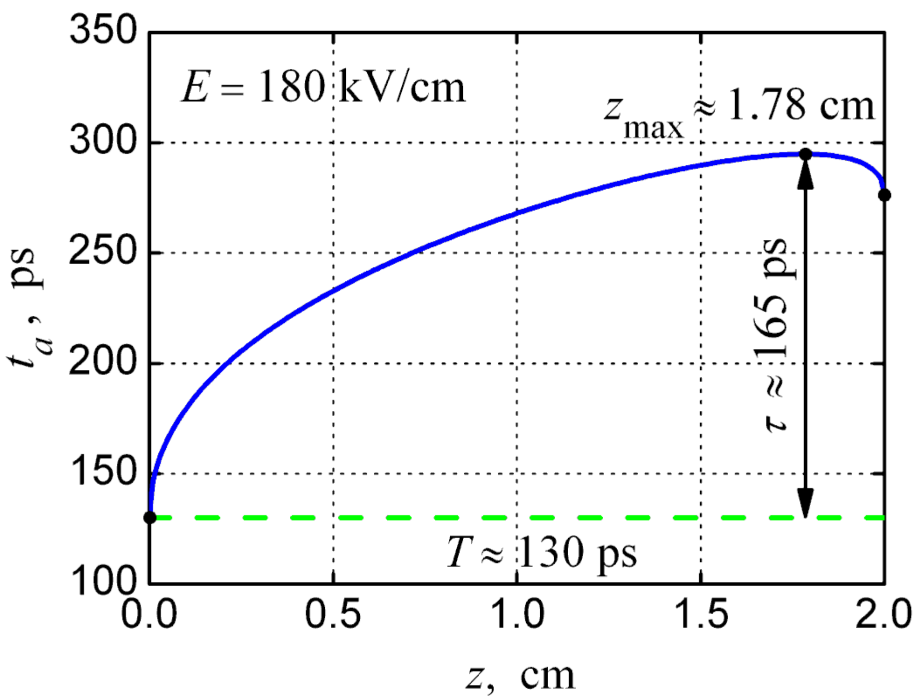


Figure: Dependence of the moment t_a when REF2 particles reach the anode on the coordinate of their creation z (solid line). The dashed line indicates the moment of reaching the anode by REF1 particles. Here $D = 2$ cm, $E = 180$ kV/cm, and $s = 2.1$.

Conclusion

We have demonstrated high sensitivity of the phenomenon of the formation of a doublet of RE flows to the significant number of interrelated factors. Obviously, an important role is played by the characteristics of REF1: the charge that it carries and its energy spectrum. The experiments shown that the amplitude of the voltage pulse, the steepness of its front, and the inter-electrode distance have a significant effect on REF2. These factors influence the evolution of the field in the gap and the character of propagation of the ionization wave through it. The effect of the ionization wave on the studied phenomena was purposefully studied in a series of experiments with an additional electrode. This electrode cuts off both REF2 and the thermal electrons in the ionization wave propagating from the cathode. In fact, the discharge was ignited downstream of the additional Al or Ta electrode due to (i) the injection of REs through it, or (ii) due to bremsstrahlung photons generated in it by REF1.

Also, we have discussed several interrelated scenarios of the formation of a dip in the total REF, i.e. its separation into a doublet. The main ideas that make it possible to explain the appearance of the second peak of the RE current at the anode are (i) the effect of “grouping” of secondary REs at the anode, according to which electrons created at different points of the gap reach the anode practically at the same time, and also (ii) the assumption that REF2 propagates in a reduced electric field, which ensures its lag relative to REF1.

Thank you for attention!