Analysis of the Minimum Duration of the Runaway Electron Flow in an Air Electrode Gap

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Runaway electrons

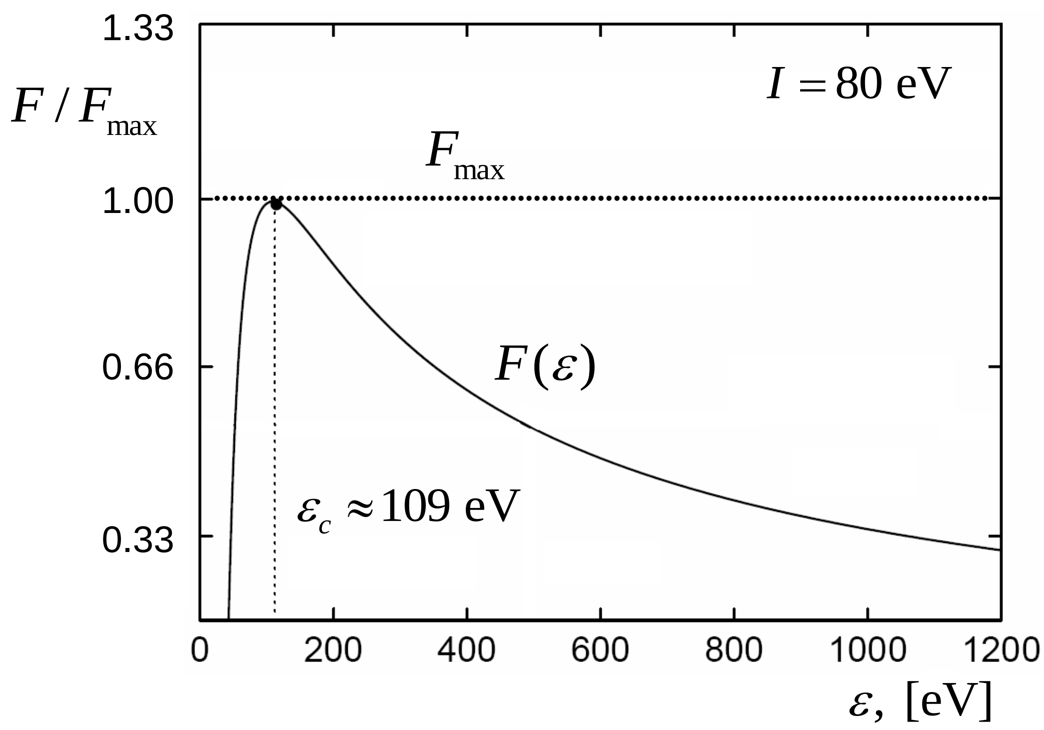
At high electric fields, the energy gained by free electrons in directional motion through a gas can be greater than the energy lost in inelastic collisions with molecules. These energetic electrons are continuously accelerated, becoming runaway electrons (REs). Their energy is comparable to the energy they would gain if they were accelerated in vacuum.

The runaway phenomenon is possible due to the fact that the friction force F acting on the electron in the gas is limited from above: the dependence of F on the electron kinetic energy ε has a maximum of $F_{\text{max}} = 4\pi Z e^4 n / \mathrm{e} I$ at $\varepsilon_c = \mathrm{e}\, I/2$.

Here we use the non-relativistic Bethe formula,

$$F(\varepsilon) = \frac{2\pi Z e^4 n}{\varepsilon} \ln\left(\frac{2\varepsilon}{I}\right),$$

where Z is the number of electrons in a neutral gas molecule, n is the concentration of molecules, I is the average inelastic loss energy, and e = 2.712 is the base of the natural logarithm.



Critical electric field

Free electrons pass from the drift mode into the runaway mode if the applied electric field exceeds the critical value

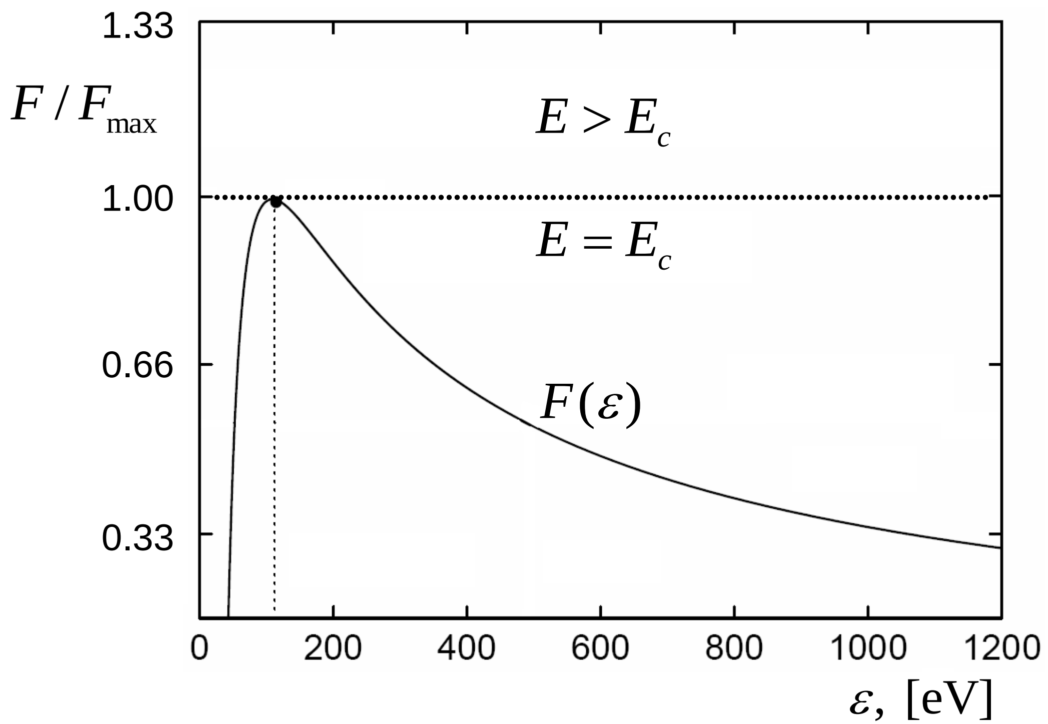
$$\boxed{E_c = F_{\max}/e = 4\pi Z e^3 n / \mathrm{e}I.}$$

In terms of the gas pressure p, this yields

$$\boxed{E_c \approx 3.4\times 10^3\, pZ/I.}$$

For nitrogen (Z = 14), we can take I = 80 eV for estimates. Then the friction force is maximum at ε_c = 109 eV. Under normal conditions ($p = 760$ Torr),

$$\boxed{E_c \approx 450 \text{ kV/cm.}}$$



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$T_{RE} < 400$ ps

↓

$T_{RE} \sim 200$ ps

↓

$T_{RE} < 50$ ps

↓

$T_{RE} \sim 40$ ps

↓

$T_{RE} \sim 25$ ps

↓

$T_{RE} < 10$ ps

Motivation

One can conclude that the RE current bursts recorded to date were as short as dictated by the bandwidth of the diagnostic used. An increase in the measurement accuracy led to a decrease in the recorded RE flow pulse duration T_{RE}.

The question arises:

How actually short is the runaway electron flow in an air electrode gap?

To answer this question, it is necessary to identify the fundamental elementary process responsible for the generation and termination of REs. The present work is devoted to this problem.

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↓

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↓

$T_{RE} < 10$ ps

↓

$T_{RE} = ???$

1. Experimental setup

A voltage pulse U_{TL} with adjustable amplitude produced by a RADAN-type generator was applied to the gap via a transmission line (TL).

We apply the conical cathode with a tip radius $R \approx 100$ μm; the gap spacing D is chosen to be 6 mm. The field strength at the cone tip is more than ten times higher than that in the major part of the gap. Also, the field strength is enhanced tenfold at submicron protrusions having the scale of $r \sim 100$ nm on the cathode surface. At the protrusions, the electric field exceeds ~10 MV/cm, which is sufficient for the field electron emission onset.

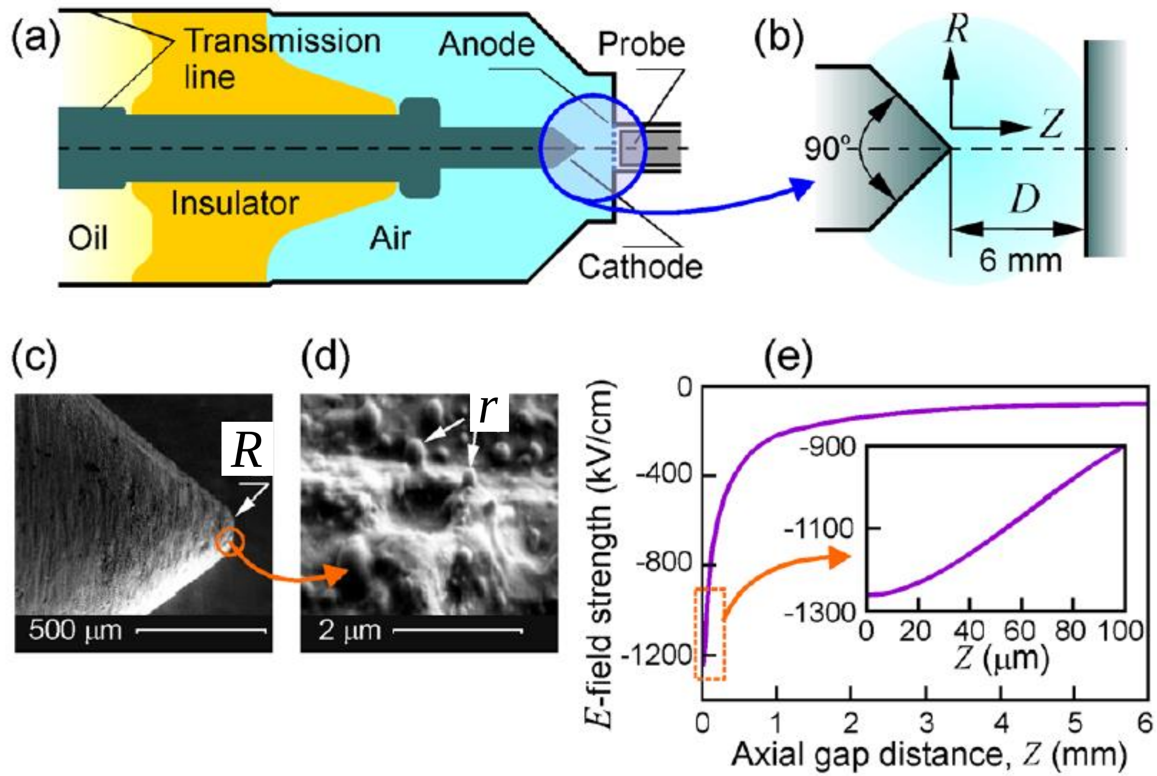
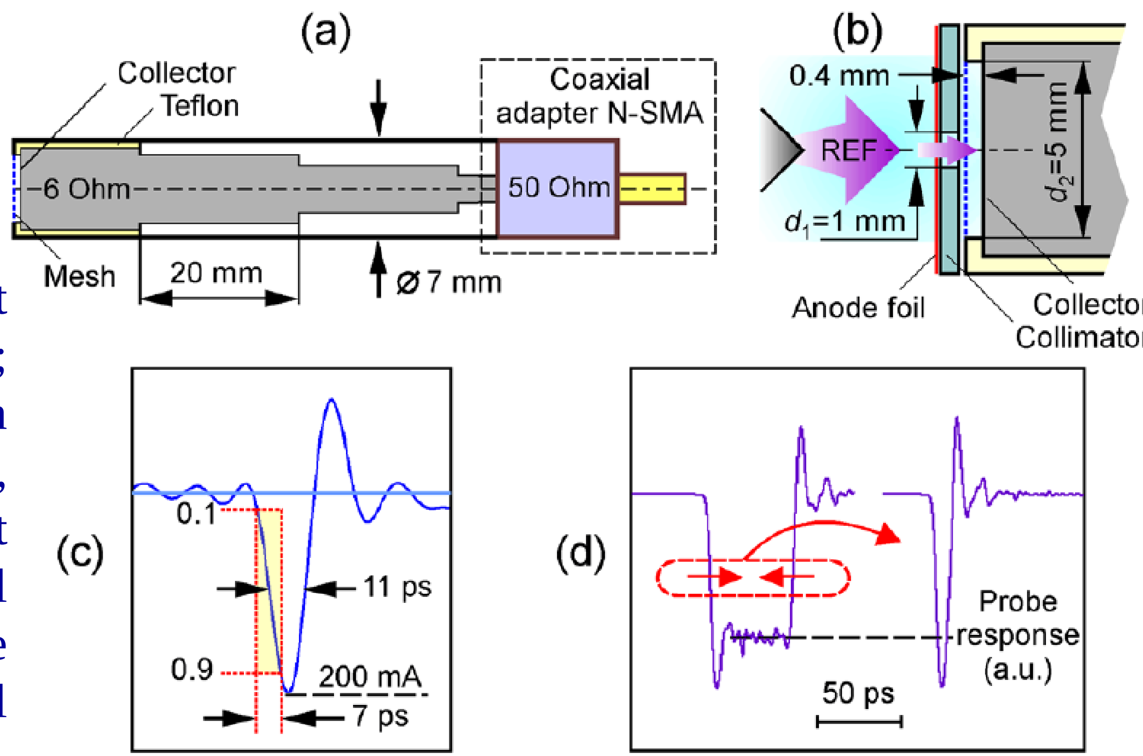


Figure: (a) Art scheme of the experimental setup; (b) zoom of the cathode-anode gap; (c) the cathode tip and (d) its zoom after the generator shot; (e) the simulated E-field distribution along the gap axis for a cathode potential of –100 kV.

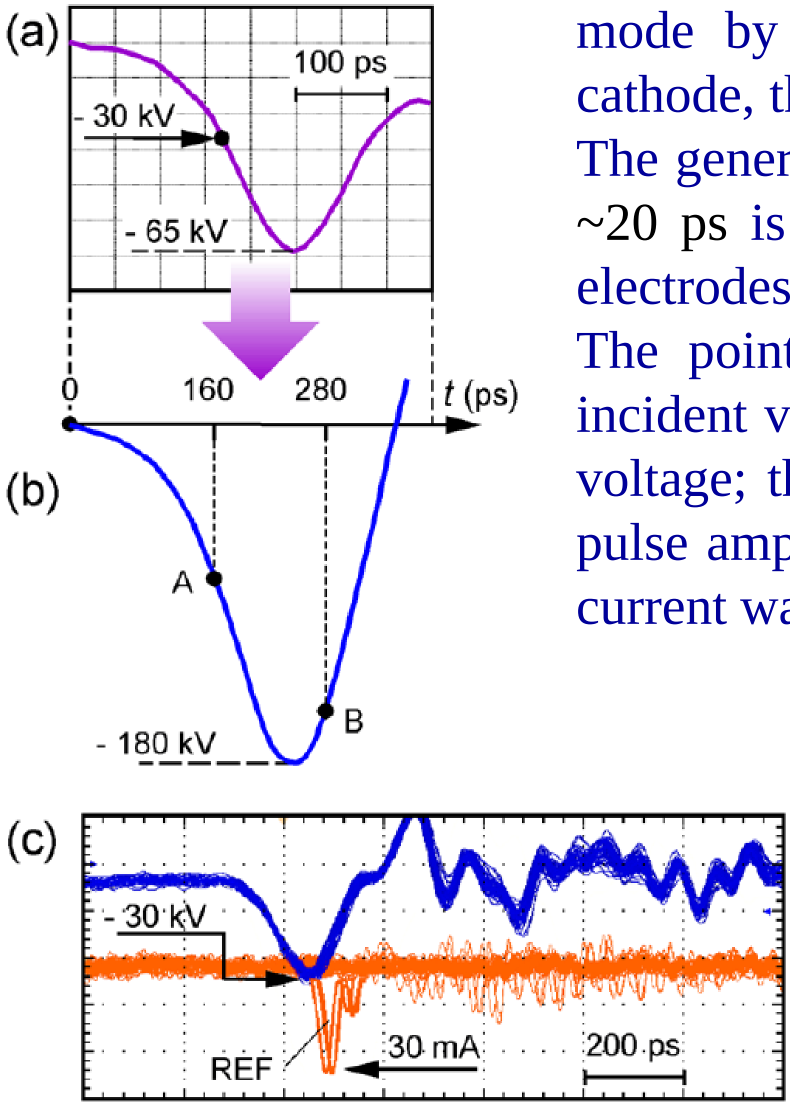
2. Experimental setup

REEs were collected by the probe downstream of the anode foil with the electron cutoff energy estimated as ~80 keV in the paraxial area with a radius of $r_h \approx 0.5$ mm defined by the collimator hole. Such a geometry of the probe provides a minimum rise in recorded RE current leading edge estimated as $r_h/c \approx 2$ ps because of the limited time of electron charge spreading (here c stands for the light velocity) from the collector. A positive burst in the RE current signal is caused by the mismatch of the lines, namely, the 6-Ω input section of the stepped coaxial line and the disk line (collector-to-mesh). Similar bursts were observed in simulations of the probe response (KARAT code).



<u>Figure</u>: Layout of the current probe (a) and its collector unit (b); (c) RE flow current waveform (recorder: Keysight DSAZ594A, 59 GHz; 160 Gs/s, ≈ 7 ps transient response); (d) results of numerical simulations of the probe response to current pulses of rise/top/fall duration of 5/50/5 and 5/5/5 ps.

1. Experimental results

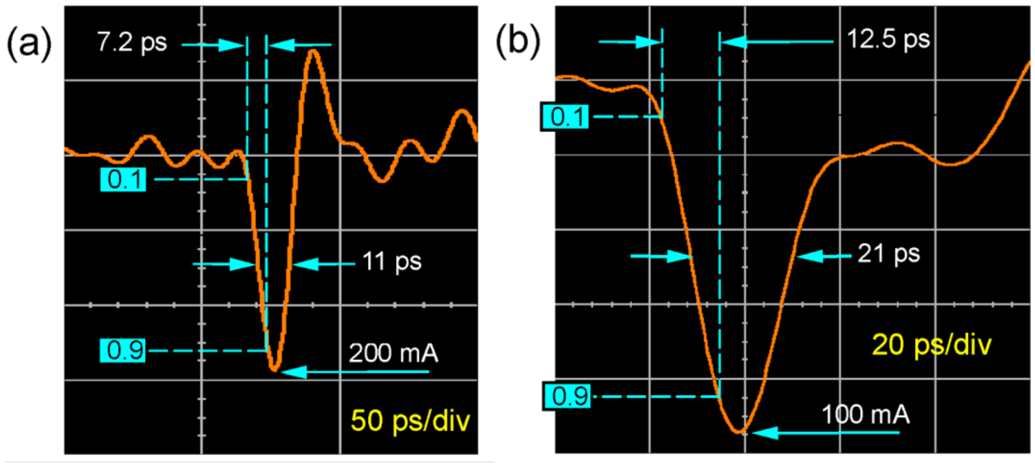


The shape of the voltage pulse was simulated in idle mode by the KARAT code [V.P. Tarakanov]. At the cathode, the pulse amplitude was increased in ~2.7 times. The generation of REs starts at the point A (its spread of ~20 ps is about half the RE time-of-flight between the electrodes). The supply voltage amplitude is –180 kV. The point A corresponds to –30 kV in terms of the incident voltage pulse and to –80 kV in terms of the gap voltage; this value was found by decreasing the voltage pulse amplitude to the threshold value for which the RE current was not detected.

<u>Figure:</u> (a) Waveform of the voltage across the 44-Ω TL; (b) simulated waveform of the voltage pulse delivered to the cathode; (c) RE flow generation threshold (three RE bursts in series of 50 shots) detected with the voltage amplitude decrease (in absolute value). Recorder: Tektronix DPO73304D (33 GHz; 100 Gs/s, 12.5 ps transient response).

2. Experimental results

Figure: The RE current waveforms for (a) conical cathode and (b) tubular cathode, mesh anode, no collimator.



The observed value of the RE current rise time was ~7 ps. The registered full width at half maximum (FWHM) for RE flow was ≈10 ps. This value is overestimated. The pulse duration hardly exceeds the oscilloscope transient response of ~7 ps. It is clear that the amplitudes of RE current bursts are recorded with an error. The total charge carried by REs is a more conservative value. This charge was $\approx 2 \cdot 10^{-3}$ nC, which corresponds to $\approx 10^{7}$ particles.

For the cathodes with a long emissive edge (blades and tubes), the total RE flow is the sum of individual ultrashort RE flows generated at different times in different places. This will inevitably result in broadening of the RE current pulse; see also [1].

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1. Theoretical model

As the basis for constructing the theory of gas breakdown by subnanosecond voltage pulses in the actual geometry of the gap, we use a quasi-2D modification [1] of the 1D kinetic model of electron transport proposed in [2,3].

The electron distribution function (EDF) f obeys the 1D relativistic Boltzmann equation with a right-hand side describing the collision processes,

$$\gamma\left(\frac{\partial f(z,p,t)}{\partial t}+\frac{p}{m\gamma}\frac{\partial f(z,p,t)}{\partial z}-eE(z,t)\frac{\partial f(z,p,t)}{\partial p}\right)=-Q_{-}+Q_{+}^{f}+Q_{+}^{s}+S_{ec},$$

where e is the elementary charge, m is the electron rest mass, $p = mv\gamma$ is the relativistic momentum (v is the radial velocity), γ is the relativistic factor. The Q-terms describe ionization collisions, the S-term is responsible for the elastic collisions in the forward-backward approximation. The impact ionization and transport cross sections for nitrogen were taken from [4].

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2. Theoretical model

The electric field dynamics is described by the Ampere-Maxwell relation,

$$\varepsilon_0 \frac{\partial E(z,t)}{\partial t} = \frac{1}{S(z)\rho}\left(U_{\text{in}}(t) - \int_h^D E(z,t)dz \right) + e\int_{-\infty}^{\infty} f(z,p,t)\frac{p}{m\gamma}dp,$$

where S is the cross-sectional area of the region where the current flows. In calculation of the $S(z)$ dependence in our 1.5D model, we assume that REs move along the electric field lines. In addition, we will apply Deutsch's hypothesis [1], according to which the space charge of a current-carrying plasma affects the absolute value of an electric field but does not distort field lines. Then the geometry of the lines of force and, accordingly, of the RE streamlines can be approximately calculated from Gauss's theorem for the electric field strength in vacuum.

- Field electron emission from the rough cathode surface [2];
- Discreteness of the electron emission;
- RE flow attenuation in the foil window [3].

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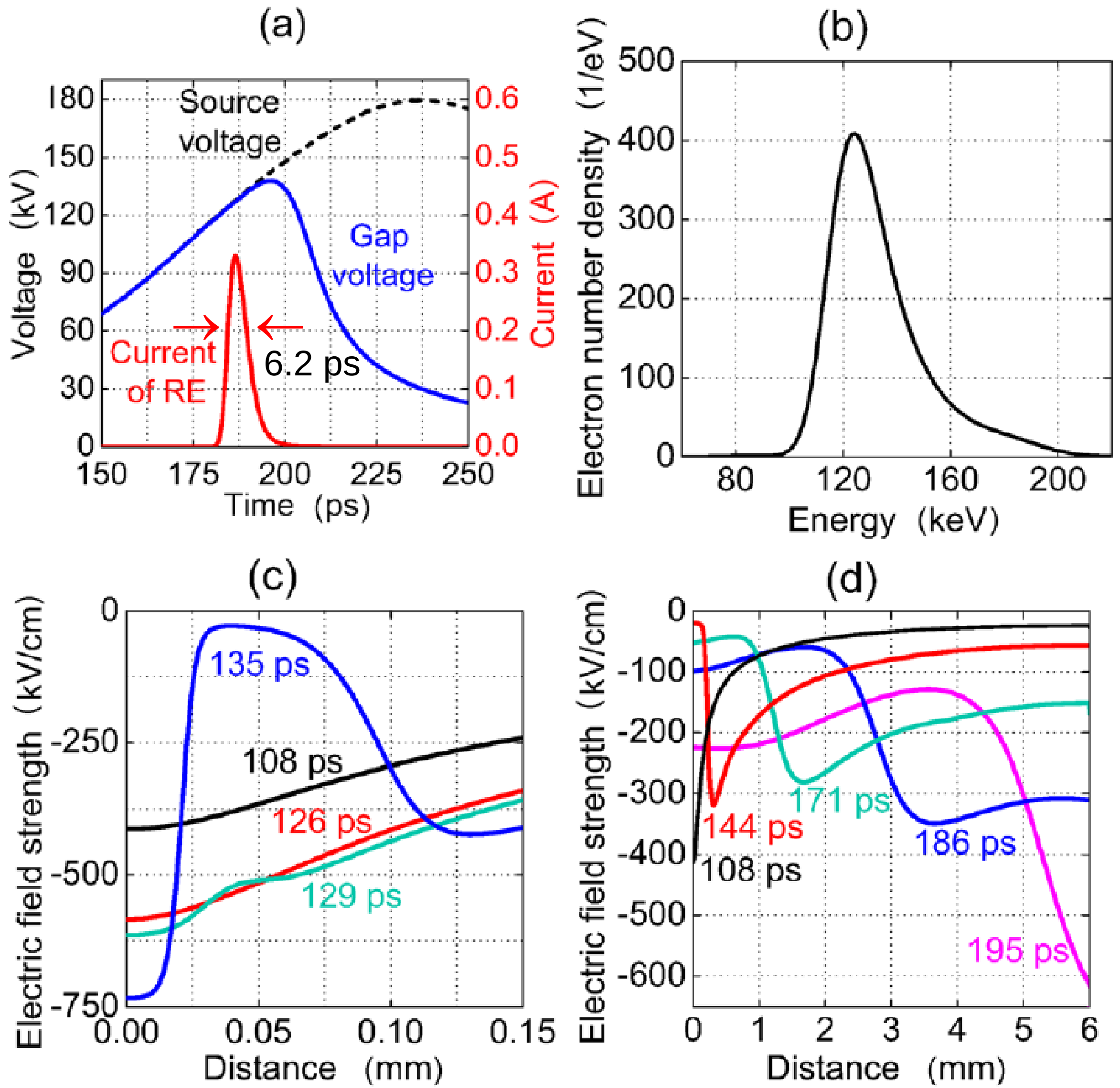
Simulation results

In our simulations, the total electric charge carried by REs ($\sim 2.2 \cdot 10^{-3}$ nC) practically coincides with the experimental data ($\sim 2 \cdot 10^{-3}$ nC).



<u>Figure:</u> (a) Waveforms of the gap voltage (in absolute value) and RE current (FWHM of 6.2 ps); (b) energy spectrum of electrons at the anode; the electric field strength distributions near the cathode (c) and in the entire gap (d) at different times.

RE flow generation and termination

From the EDF, one can see a distinct region in which the number of REs is maximum and a thinning neck connecting REs with the ionization wave front. Thus, the process of RE generation practically terminates less than 10 ps after the time at which the plasma density becomes quite high, and this just determines the RE current pulse FWHM equal to ~6.2 ps.

It should be noted that a similar scenario was described in [1] for the initial stage of gas discharge in the "tubular-edge cathode – planar-anode" gap and further developed in [2-4]. According to [1], T_{RE} amounts to 10-20 ps, which is qualitatively consistent with our conclusions.

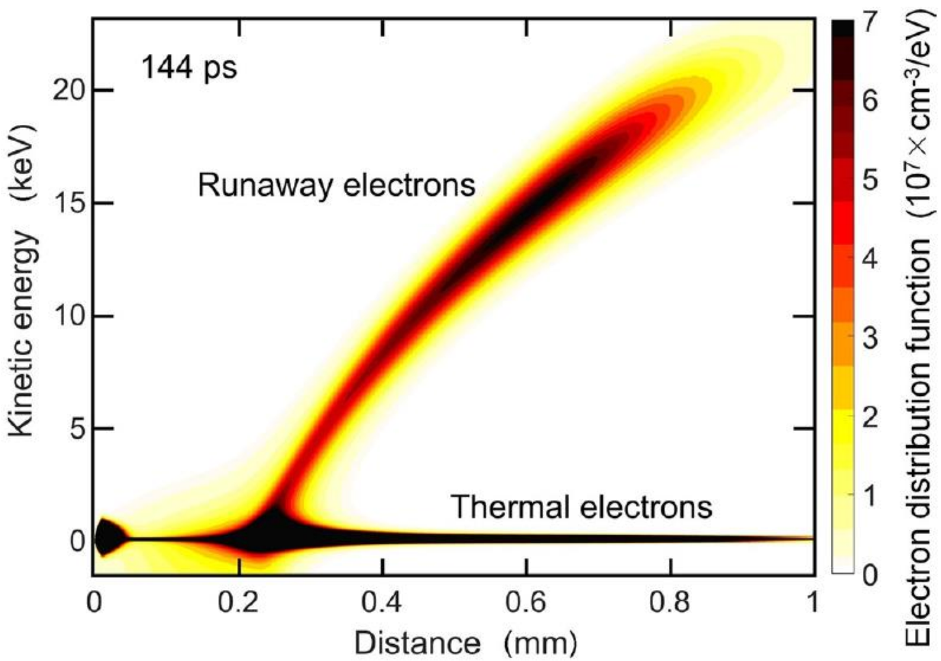


Figure: The electron distribution function (EDF) at the 144th picosecond.

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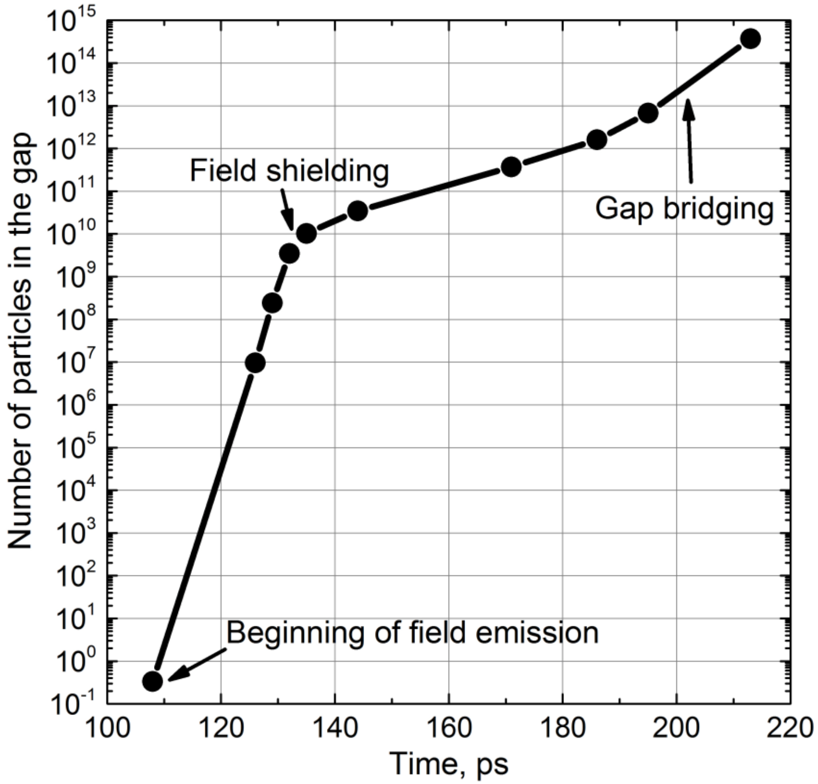
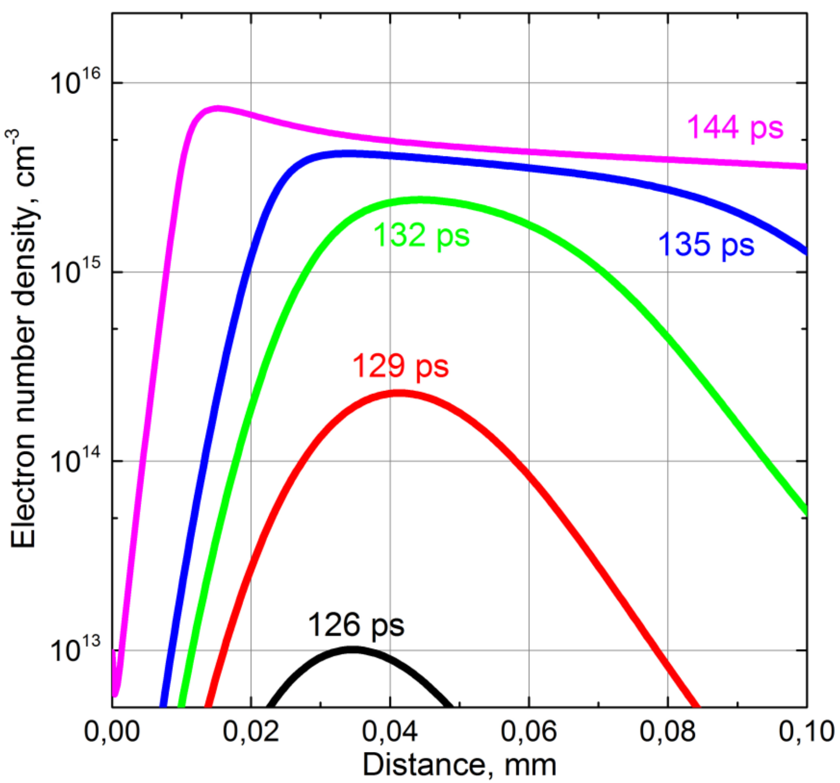
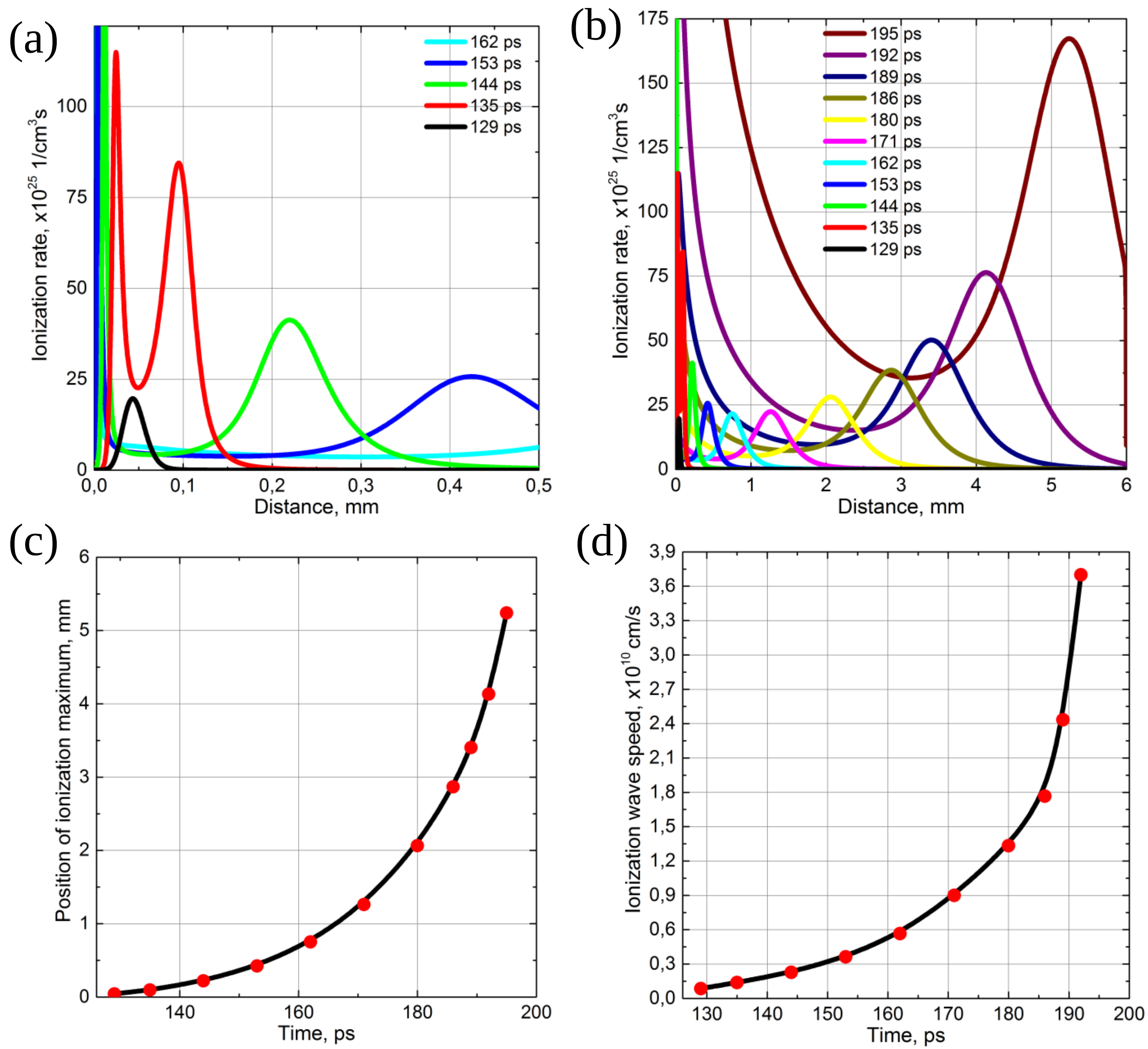
Multiplication of free electrons





Propagation of the ionization wave

Figure: Ionization rate distributions (a), (b); (c) position of the ionization wave front (maximum of the ionization rate), and (d) its phase velocity.



Simulation results: sequence of main events

Field emission onset:

$t \approx 110$ ps

RE flow generation in the near-cathode region:

$t \approx 135\text{-}145$ ps

RE current burst at the anode:

$t \approx 185\text{-}195$ ps

Gap voltage drops due to bridging of the gap by the plasma:

$t \approx 195\text{-}220$ ps

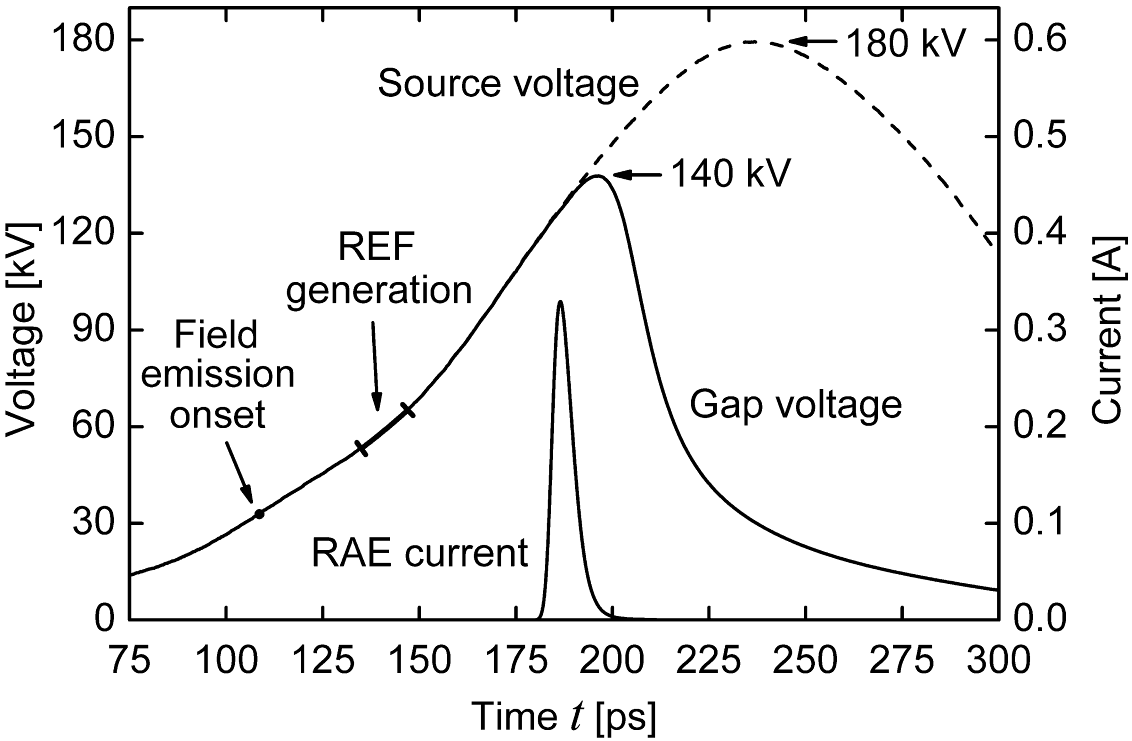


Figure: Model waveform of the source voltage (in absolute value); simulated waveforms of the gap voltage and RE current.

Estimation of RE flow minimal duration

Free electrons in an electrode gap can be divided into two groups: high-energy REs and low-energy thermal electrons moving with a drift velocity V_e, which is determined by the gas properties (its sort and pressure) and the field strength E.

The behavior of the low-energy electron ensemble is largely determined by the impact ionization. This process is characterized by the first Townsend ionization coefficient a depending, as V_e, on E and the gas properties. Its characteristic time, i.e., the mean interval over which the number of free electrons increases in ~2.72 times, is given by the following estimation: $t_i = 1/(V_e\alpha)$.

We are interested in the process of RE generation during which part of initially thermal electrons become REs. This is possible if $E \approx E_c$. Then the characteristic time scale of the problem is

$$\boxed{t_{\mathrm{RE}} \equiv t_i(E_c) = 1/[V_e(E_c)\alpha(E_c)].}$$

The time t_{RE} introduced in this way combines the characteristics of both thermal (α and V_e) and runaway (E_c) electrons. It can be supposed that this time scale governs the RE flow generation/termination. Then, the minimum RE flow duration T_{RE} will also be limited by this elementary time.

For nitrogen at atmospheric pressure, we can roughly estimate $\alpha \approx 5\cdot10^3$ cm^{-1} and $V_e \approx 8\cdot10^7$ cm/s for $E = E_c \approx 450$ kV/cm and, hence, we get $t_{\mathrm{RE}} \approx 2.4$ ps, which corresponds well to the described scenario of the RE flow generation/termination.

Conclusion

We have shown that the RE flow generated in a high-voltage (the voltage rise rate of up to 1.5 MV/ns) air-filled electrode gap with a strongly nonuniform electric field contains a high-energy electron fraction of duration not more than 10 ps. This is essentially less than the characteristic time-of-flight of REs to the anode. Our analysis shows that the RE flow duration is defined by the elementary time t_{RE} of the order of several picoseconds, viz., by the time scale of impact ionization processes calculated at the critical field E_c of electron runaway. At first, the time t_{RE} is the characteristic time for growth of the amount of free electrons close to the cathode tip. A part of these electrons become REs if $E \approx E_c$. Secondly, the same time t_{RE} governs the RE flow termination when the ionization wave reaches the peripheral region with a relatively low electric field and, hence, the probability of RE generation becomes negligible.

Thank you
for attention!