Measurement of the duration of runaway current pulses using measuring equipment with bandwidths up to 50 GHz

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Abstract. The duration of current pulses of runaway electrons generated during the formation of a nanosecond discharge in air in a sharply inhomogeneous electric field was measured using measuring equipment with a bandwidth of 50 GHz. The influence of the gas pressure and the shape of a cathode on the duration of the RE current pulses is investigated. Current pulses with full width at half maximum of 16–28 ps were recorded, depending on the conditions.

1. Introduction

The generation of runaway electrons (REs) during the formation of nanosecond gas discharges in inhomogeneous electric fields gradually became an ordinary phenomenon as experimental data accumulated in a wide range of conditions and theoretical models developed [1–7]. The values of the critical electric field strength for various gases, the maximum amplitudes of currents and energies of REs for various conditions (∼ 10⁴–10⁵ V, ∼ 1–10⁶ Pa, ∼ 10⁻³–10⁻¹ m) were determined. However, there are still discussions about the shortest duration of the RE current pulses for a discharge, in particular in air. The current pulse with full width at half maximum (FWHM) of 45 ps was recorded during a high-voltage nanosecond discharge in air and using an oscilloscope with a bandwidth of up to 15 GHz [8]. The results of numerical simulation [9] for similar conditions show that the pulse duration can reach 10–20 ps and limited by plasma screening of the electric field in the vicinity of a cathode. In [10], a RE current pulse with FWHM of 25 ps was recorded when using an oscilloscope with a bandwidth of up to 33 GHz. The authors note that the shape of a cathode and the diameter of a diaphragm placed in front of a collector affect the duration of RE current pulses. In a recent studies [11], the RE current pulse with FWHM of 11 ps was recorded when using an oscilloscope with a bandwidth of up to 59 GHz. At the same time, the results of numerical simulation performed in [11] show that the pulse duration can reach units of picoseconds.

The purpose of present studies was to determine the duration of RE current pulses generated during a nanosecond discharge in air using the measuring equipment with a bandwidth of up to 50 GHz and how a decrease in an air pressure and a change in the cathode shape affect the duration of RE current pulses.

2. Experimental setup and measuring equipment

Experiments were carried out on a setup shown in figure 1 (a). A GIN-55-1 generator produced a negative voltage pulse (figure 1 (b)) which was applied across a point-to-plane gap in a gas discharge
chamber via a 75-Ω high voltage cable and a 75-Ω transmission line equipped with a capacitive voltage divider (CVD). Two different pointed electrodes were used as a cathode. The first one was made of a steel and had a conical shape (figure 1 (a)) like in [11] in order to compare data. The second cathode was made of a stainless steel sewing needle with the radius of curvature of a needle tip of 75 µm (not shown in figure 1 (a)). A grounded electrode was made of a 0.2-mm copper foil with a 1-mm hole in the center. The interelectrode distance was 6 mm.

A current of REs was measured with a collector made of a panel SMA connector which was mounted on a 1-mm thick copper disc with a 1-mm hole in the center. This copper disc acted as a diaphragm. Aluminum foils of various thickness (10 and 50 µm) could be placed between the grounded electrode and the diaphragm (figure 1 (a)). This made it possible to filter electrons by energy.

A SUCOFLEX 101PEA (HUBER SUHNER) microwave cable assemble applicable in frequencies up to 50 GHz was applied to transmit the RE beam current pulses to an ATI channel of a Tektronix DPO75002SX oscilloscope (50 GHz, 200 GS/s). No limiters and/or attenuators were used to provide maximal bandwidth. The oscilloscope was triggered by the CVD signal arriving to an AUX input.

The gas discharge chamber was pumped out with a fore vacuum pump and then filled with air. The pressure was varied in the range of 25–100 kPa. Experiments at lower pressures were not carried out in order to exclude the risk of damage to the oscilloscope due to an increase in the amplitude of the RE current.

![Diagram of experimental setup](image)

**Figure 1.** (a) Experimental setup and (b) high voltage pulse at a matched load.

3. Results and discussion

When applying the voltage pulse across the cone-to-plane gap, a diffuse discharge is formed. The breakdown development and the formation of the diffuse discharge were studied earlier [12] with using ICCD and streak cameras. It was found that a large diameter streamer starts to form in the vicinity of the pointed electrode and bridges the gap in 0.1–0.2 ns. By simultaneously measuring the current caused by the appearance and movement of a streamer and the RE current [13], it was found that REs are generated in the vicinity of the pointed electrode at the moment of streamer initiation.

Figure 2 shows the waveforms of current of REs passed through the aluminum foil with a thickness of 10 µm in absolute values and normalized to the maximum one as well as the FWHM of the RE beam current pulses for different implementations at an air pressure of 25 and 100 kPa. It can be seen that the pulse duration varies from implementation to implementation. The amplitude of the RE current pulses also varies from implementation to implementation. The figure 2 (a) shows waveforms of the RE current pulses whose amplitudes are close to the average value. No relationship was found between the amplitude and FWHM of the RE current pulses. The average FWHM for a discharge in air at a pressure of 100 kPa is ≈ 19 ps. The minimum FWHM reaches ≈ 16 ps. This value is greater than that measured in [11]. However, the voltage across the gap in [11] was more than 2 times higher.

A decrease in an air pressure leads to a slight increase in FWHM (figure 2 (d) vs figure 2 (c)). This
may be due to the fact that with decreasing pressure, the reduced electric field at the front of the forming plasma still continues to exceed the critical value required for the runaway mode for a short time, limited by an increase in the streamer diameter. Previous studies have shown that a decrease in pressure does not significantly affect the strength of the electric field at the front of the streamer [14]; only the reduced electric field strength and streamer velocity increase.

Figure 2. (a, b) Waveforms and (c, d) FWHM of RE beam current pulses at various pressures of air. Cone-to-plane gap with \( d = 6 \text{ mm} \). 10-\( \mu \text{m} \) aluminum foil was used as a filter.

In the experiment, it was also determined how FWHM changes depending on the thickness of the aluminum foil (figure 1 (a)), which is an energy filter for REs. Figure 3 shows the corresponding waveforms of the RE current pulses whose amplitudes are close to the average values. The gap was filled with air at a pressure of 100 kPa. No significant differences in FWHM were found in a series of several dozen discharge implementations.

However, it was found that a tail is observed on the waveforms of the RE current pulses recorded for the case when the foil is absent. In this case, there are no obstacles for REs on the way from the cathode to the collector (see figure 1 (a)). The total duration of the RE current pulse, taking into account the tail, is of the same order of magnitude as the time required to bridge the gap by the plasma (0.1–0.2 ns [12]). The tail length decreases with increasing electron energy cutoff. The tail is absent only when using the Al foil with a thickness of 50 \( \mu \text{m} \). It follows from this that the tail is formed by REs with a relatively low energy. These REs could have been generated during the streamer propagation.
Figure 3. Waveforms of RE beam current pulses when using various aluminum foils as a filter. Cone-to-plane gap with $d = 6$ mm. Air at a pressure of 100 kPa.

Figure 4. (a, b) Waveforms and (c, d) FWHM of RE beam current pulses at applying various cathodes (cone vs needle). $d = 6$ mm. 10-$\mu$m aluminum foil was used as a filter.

The influence of the shape of the cathode on FWHM was also studied. Figure 4 shows the waveforms of the RE current pulses recorded for two different cathodes: needle and cone. From general considerations, it is clear that the electric field strength near the surface of the needle cathode is several times higher than on the surface of the cone. In a sense, it is equivalent to a decrease in air...
pressure by the corresponding number of times (figure 2). It can be seen from the figure 4 that FWHM is more when using the needle cathode. This can also be explained by the persistence of a high reduced electric field strength at the front of the incipient plasma for a short time until the electric field strength decreases due to an increase in the streamer diameter.

4. Conclusion
Studies show that in a nanosecond discharge in a sharply inhomogeneous electric field, REs are generated within an extremely short period of time. Using measuring equipment with a bandwidth of up to 50 GHz, the RE current pulses of up to 16 ps in FWHM were recorded. It was found that the pulse duration increases with an increase in the reduced electric field strength in the vicinity of the pointed electrode at the same voltage across the gap.

It was found that the RE current pulse contains a tail of relatively low-energy electrons, the length of which is of the same order of magnitude as the time required to bridge the gap by the plasma.

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