Measuring the expansion velocity of plasma formed during electrical breakdown along an exploding al foil in a medium of desorbed gases

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Abstract. This paper reflects the experimental results on the measurement of the expansion rate of the plasma formed during an electrical breakdown along the exploding Al foil. Electric breakdown took place in a mixture of gases that were desorbed from the surface of the foil as it heated by a current passing. Aluminum foil size: length 20 mm, thickness 6 µm and the width was varied in the range from 0.93 mm to 1.05 mm. The explosion of the foil was carried out by a sinusoidal current with an oscillation period of 1780 ns. The amplitude of the current \( I \) varied depending upon the voltage charge \( U_{\text{ch}} = 10, 20 \) and \( 30 \) kV) of 0.25 µF capacitor was about 6.5, 14 and 22 kA accordingly. The measurements of the expansion rate of the plasma was carried out using three electrical probes located beneath a ground potential, near the edges and in the middle of the exploding foil, in the process, the distance from the foil to the electrical probe was varied from 2 mm to 16 mm. In the experiment we measured the time of the signal appearance relative to the moment of electrical breakdown occurrence along the foil. The rate of plasma expansion was calculated by measuring the time of plasma span from the foil to the probe with consideration of the distance to the probes.

1. Introduction

It is known that the explosion of conductors (wires and foils) in vacuum is accompanied by the formation of a plasma corona around the exploding conductor. The formation of plasma around the exploding conductor leads to a voltage drop applied to one of the edges of the conductor. Several studies [1, 2], demonstrated that synchronously with the voltage drop, an intense flash of radiation occurs in a wide spectral range (from infrared to ultraviolet) that indicates the formation of a layer of ionized plasma corona. The plasma formed around the exploding conductor expands with gathering velocity [3].

The expansion rate of corona has been measured by different authors with using different methods and approaches. The assessment has been made based on usage of laser shadowgram [4], have shown that the corona dense part expands at a rate of \( 0.8\times10^6 \) cm\( \cdot \)s\(^{-1} \). These authors [5] used another approach. In the experiments on the explosion of fine wires the visible light emitted by the exploded conductors was recorded using a fast photodiode. Then the authors carried out a comparison of the form of light radiation obtained by the explosion of one Al conductor and two parallel Al conductors exploded simultaneously. The conductors were located at a distance of 0.2 cm from each other. When two plasma...
flows collided from each of the exploding conductors, a sharp increase in the radiation occurred. The rate of the corona expansion that has been valued at the time of a sharp increases of radiation was also equal to $0.8\times10^6 \text{ cm}\cdot\text{s}^{-1}$. According to the authors [5], the rate of the corona "reconstructed by optical diagnostics corresponds to a relatively high density of the fast-expanding corona". To measure a velocity of low density plasma authors [5] placed an exploding wire inside the return current cylinder with a diameter of 5 cm. The oscillography of input and output currents showed that the output current completely stopped after 500 ns at the moment when the current appeared through the return current cylinder. This fact indicates that the plasma corona completely shunted the current through the exploding conductor. The velocity of the low density plasma measured by this technique was $(0.5–1)\times10^7 \text{ cm}\cdot\text{s}^{-1}$.

The measurements of the velocity of plasma corona using optical frame camera [6] gave the rate of expansion $(3–4)\times10^6 \text{ cm}\cdot\text{s}^{-1}$. Duselis and Kusse [7] measured the time delay between the voltage drop and the beginning of the current flowing through the circuit of an additional ring electrode. The exploded wire was installed along the axis of the ring; the diameter of the ring was 1.4 mm. Based on these measurements the maximal expansion rate of plasma corona was estimated at $1.4\times10^6 \text{ cm}\cdot\text{s}^{-1}$.

In the work [8] investigations of the expansion rate of the plasma corona were carried out for an exploded Al and W conductors at a current density of $1\times10^8–1.4\times10^8 \text{ A}\cdot\text{cm}^{-2}$. The conductors of W exploded in two modes: with pre-heating and without. The experiments showed that the expansion rate of the plasma corona without pre-heating is independent of the wire material. The expansion rate for both aluminum and tungsten conductors that were exploded without pre-heating was $(7 \pm 0.5)\times10^6 \text{ cm/sec}$ in case of a capacitor charging voltage of $U_{c} = 10 \text{ kV}$, $(9 \pm 0.5)\times10^6 \text{ cm}\cdot\text{s}^{-1}$ in case of $U_{c} = 20 \text{ kV}$ and $(1.1\pm0.6)\times10^7 \text{ cm}\cdot\text{s}^{-1}$ in case of $U_{c} = 30 \text{ kV}$. Experiments with the pre-heated (1880ºK) tungsten conductors have shown that the expansion rate of the corona decreased by about 30% when removing the desorbed gas and it was $4.2\times10^6$ and $9\times10^6 \text{ cm}\cdot\text{s}^{-1}$ when a charging voltage was $U_{c} = 10$ и $30 \text{ kV}$, respectively.

2. Experimental setup and the methodology of experiments
The foil explosion took place by means of pulse-power generator WEG-2 which is schematically an $RLC$ circuit with the capacitor $C_{c} = 0.238 \text{ \mu F}$. The inductance of the generator together with the foil explosion circuit was $L_{c} = 341 \text{ nH}$, while the inductance of the part of the electrical circuit at which the measurement of the voltage drop on the foil have made was $L_{f} = 150 \text{ nH}$. The replacement of the foil in a copper wire with a diameter of 1 mm the resistance of the circuit was $R_{c} = 0.12 \text{ Ohm}$. A high-pressure trigger was used for the commutation of the charged capacitor to the generator electrical circuit which was built into the capacitor (capacitor-switch assembly). The magnitude of current flowing in the circuit of the exploding conductor was calculated by integrating an electrical signal with a B-dot1 (see figure 1) installed in the immediate vicinity of the mounting location of the conductor under consideration. The sensitivity of the B-dot1 was determined in the short circuit (SC) mode, in which, along with the B-dot1, a calibrated shunt was used. In SC mode, the load was a copper wire 1 mm in diameter, 2 cm long.

The amplitude of the flowing through the conductor current $I$ was varied depending on the charging voltage of the capacitor ($U_{c} = 10$, $20$ and $30 \text{ kV}$) and it was about $6.5$, $14$ and $22 \text{ kA}$, respectively. The charging voltage of the WEG-2 pulse-power generator was varied to determine whether the energy that was supplied to the exploding foil until the voltage drop had influence on the expansion rate of the plasma corona. The current had a sinusoidal form with a period of oscillation $T = 1790 \text{ ns}$. When calculating the value of the voltage drop only on the foil, the inductive component was subtracted from the high-voltage divider signal (the resistance of the upper arm voltage divider was 500 Ohms and the resistance of the lower arm voltage divider was 1 Ohm). The high-voltage electrode had a negative polarity.

For the experiments the aluminum foil was used which had the size of $l_{foil} = 21 \text{ mm}$ the length, $a_{foil} = 0.99 \pm 0.06 \text{ mm}$ the width, $b_{foil} = 6 \mu m$ the thickness. The foil was assembled inside the dielectric holder that was installed between the electrodes (figure 1). The foil was soldered to copper electrodes (there were installed inside the holder) using flux for aluminum soldering. After assembly, the foil
holder was thoroughly washed with water then alcohol and it placed in a vacuum chamber which was pumped out by a turbo molecular pump up to pressure of \((4 \pm 1) \times 10^{-5}\) Torr.

The measurement of the velocity of the plasma expansion was carried out by means of one electrical probe which was the grounded collector of current. When the boundary of the current-carrying plasma reached the location of the electrical probe the part of the current flowing through the expanding plasma corona began to flow in the circuit of electrical probes. Using a B-dot\(_2\), a probe current derivative was measured on the TDS-2024 scope. The electric probe was located in the middle of the exploding foil within the distance \(d\) from the foil edge. The value of \(d\) was varied from 1 ± 0.25 mm to 10 ± 0.25 mm. The experimental scheme is shown in figure 1.

![Figure 1. The scheme of the experiment.](image)

3. Experimental results

A typical oscillogram of the B-dot signal (the derivative of the current), that was found during the explosion of aluminum foil when the charging voltage of the capacitor up to 20 kV (Shot#244) together with its integral (current) demonstrated in figure 2a. The typical oscillogram of the signal from the resistive voltage divider together with the voltage drop minus the inductive component of this signal demonstrated in figure 2b. The energy deposition in the exploding foil that was calculated from the current and voltage oscillograms demonstrated in figure 2b. Following the authors of [6–8], we determined the time relevant to the maximum voltage as the time of breakdown (collapse) \(t_{\text{coll}}\). Typical signal received from electric probe was located at a distance of 0.4 cm from the side face of the foil and demonstrated in figure 2c.

In the experiment, we measured the time span \(t_{\text{del}}\) from the moment of occurrence of the breakdown along the foil \(t_{\text{coll}}\) to the B-dot\(_2\) pulse maximum (figure 2c). Thus, measuring the time \(t_{\text{del}}\) of plasma flight from the foil to the probe and considering the distance to the probes \(d\), the velocity of plasma expansion was calculated \(v_{\text{pl}}\).

Table 1 presents the following parameters: the time \(t_{\text{coll}}\) from the beginning of the current through the foil to the beginning of a sharp voltage drop; the specific energy \(e_{\text{depl}}\), embedded in the exploding foil to the moment of time \(t_{\text{coll}}\); the amplitude of the voltage drop on the foil (minus the inductive component) \(U_{\text{coll}}\). The parameters given in table 1 averaged over 17 shots. The input energy \(\varepsilon\) was determined by integrating the power dissipated in the aluminum foil during the period between the start time of the current flow through the foil and the time \(t_{\text{coll}}\) (figure 2). These characteristics are given for the charging
voltage of the capacitor WEG-2 $U_{ch} = 20$ kV, however, the electric probe was not installed. These measurements were carried out to make sure that the electrical probe does not have a noticeable effect on the explosion of the foil under research. Table 2 presented the same characteristics of aluminum foil explosion for different voltages $U_{ch}$ of the charging capacitor of the current pulse-power generator WEG-2 but with the installed electric probe. The characteristics in table 2 were averaged over 10 shots made for each of the three modes.

As may be seen from tables 1 and 2 the electrical probe developed to measure the time of plasma expansion relative to moment $t_{coll}$ (installed directly in the body of the holder insulator) does not have a noticeable effect on the process of foil explosion.

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**Table 1.** The characteristics of aluminum foils explosion with the charging voltage of the capacitor WEG-2 $U_{ch} = 20$ kV without electrical probe.

| $t_{coll}$ (ns) | $U_{coll}$ (kV) | $\varepsilon_{dep}$* (kJ·g$^{-1}$) |
|-----------------|-----------------|----------------------------------|
| 156 ± 12        | 8.3 ± 1.2       | 4.1 ± 0.6                        |

* The melting and sublimation energy of Al [9, 10] was 0.995 kJ·g$^{-1}$ and 11.9 kJ·g$^{-1}$, respectively. The enthalpy of Al was estimated for thermal capacity of 24.3 J·moll$^{-1}$·K$^{-1}$.

**Table 2.** The characteristics of aluminum foil explosion at different charging voltages of the capacitor $U_{ch}$ in the presence of electric probe.

| $U_{ch}$ (kV) | $t_{coll}$ (ns) | $U_{coll}$ (kV) | $\varepsilon_{dep}$* (kJ·g$^{-1}$) |
|---------------|-----------------|-----------------|----------------------------------|
| 10            | 258 ± 17        | 4.9 ± 0.7       | 3.2 ± 0.45                       |
| 20            | 156 ± 12        | 8.6 ± 0.8       | 4.6 ± 0.45                       |
| 30            | 126 ± 11        | 11.6 ± 1.3      | 5 ± 0.95                         |

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Figure 2. Typical waveforms are: a – B-dot$_1$ signal that was recorded during the explosion of aluminum foil at a charging voltage of the capacitor up to 20 kV (Shot#158) together with its integral (current); b - the signal from the resistive voltage divider together with the voltage drop on the exploding foil with the deduction the inductive component of this signal, as well as the energy deposition that was calculated from the current and voltage oscillograms; c – B-dot$_2$ signal.
In figure 3 the experimental values of the expansion velocity of the plasma corona formed around the exploding foil at the moment of breakdown occurrence that were obtained at $U_{ch} = 10, 20$ and $30$ kV.

![Figure 3](image.png)

**Figure 3.** Dependence of the distance traveled by plasma on time. The values of the velocity of the plasma corona expansion $v_{pl} = dx/dt$, were obtained experimentally by means of electrical probe measurements.

4. Conclusion
The probe measurements show that the expansion rate of a low-density, current-carrying plasma corona is weakly dependent of the charging voltage of the capacitor in the electrical circuit of the pulse-power generator. With an increase in the charging voltage from 10 to 30 kV, the expansion rate of the plasma corona changes from $v_{pl} = (5\pm1)\times10^6$ to $(8\pm1)\times10^6$ cm$^{-1}$s$^{-1}$. The process of energy deposition into the expanding plasma corona occurs within $20–30$ ns after the start of breakdown along the conductor and ends after the voltage across the conductor decreases to zero. After this time, the plasma propagates at an almost constant speed $v_{pl}$. The obtained values of the velocity $v_{pl}$ were correlated well with the data obtained in works [8] with the explosion of cylindrical conductors (wires). The experimental data that were obtained in the explosion of aluminum foils have shown good agreement with the findings of the authors [6] and [11], who believe that the plasma corona is formed as a result of the desorbed gas ionization. The fact that the rate of the corona expansion for exploded aluminum foils and the cylindrical conductors is almost the same due to the identical composition of the desorbed gas and the nature of desorption. It should be noted that the critical contribution of desorbed gases to the corona formation at WE in vacuum was also indicated in [12, 13].

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