INVESTIGATION OF THE PROPERTIES OF EXPLOSIVE PLASMA JETS AND THEIR INTERACTION WITH ELECTROMAGNETIC WAVE

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We present the results of experimental investigations of explosive plasma jets (PJ) formed in open space. A possibility of the radiation of pulsed electromagnetic signals with PJ is shown, and the conditions for such radiation are studied. The analysis of the experimental results for short and long PJ is given. As the jet propagates in the field of a spiral, a short-time increase of the radiated signal is observed. A linearly parametrical model of the interaction between PJ and the exciting electromagnetic signal is proposed.

1. Introduction

One has every reason to consider that the first plasma antennas were thunder lightnings, where the electric current flows through a conductive channel formed in the atmosphere and creates electromagnetic signals in ambient air. These signals were already registered at the beginning of the development of radio engineering. Suffice it to recall a thunder controller created by O.S. Popov.

A keen interest in using the plasma media as antennas has appeared as far as the 1960s. The idea of plasma antennas is based on the possibility to replace the constructive elements of ordinary antennas (vibrators, reflectors) by plasma formations. Plasma can exhibit the properties of either a metal or an insulator with respect to electromagnetic waves [1], which is used in creating the plasma antennas. Up to date, one can distinguish three tendencies in the realization of plasma antennas depending on the method used to obtain PJ:

— formation of a conductive channel in the atmosphere under the action of ionizing radiation [2, 3];

— use of plasma obtained in dielectric tubes [4—6];

— explosive methods of formation of PJ in open space [7, 8].

In the latter case, PJ are formed at the expense of chemical reactions, whose products are taken out into open space by the explosion.

In spite of a short time of the existence of explosive plasma antennas, the interest in them is conditioned by the possibility of their use for creating the compact explosive sources of electromagnetic signals [9, 10] that allow one to investigate physical processes in the upper atmosphere. In this case, the signal generator is arranged on a geophysical carrier [11], and one uses the jet of the march engine of the carrier instead of awkward antenna constructions [12].

2. Experimental Apparatus Used for the Formation of Explosive Plasma Jets and Investigation of Plasma Parameters

In order to obtain PJ in open space, one uses special generators. The most essential contribution into their development was made by M.A. Tsikulin [13]; then similar generators were constructed for a long time by V.M.Kysel'ov [14]. The basic advantages of these generators are their small dimensions and a possibility of the operative change of the plasma composition.

We have created an experimental PJ generator, whose construction is showed in Fig. 1. The principle of its operation is the following. The primary energy source is pyrocartridge *1*, whose energy is determined by the mass of the explosive substance (ES) with easily ionized impurities (Mg, Li, $CsNO_3$, etc.) and amounts to 0.6—3.1 kJ in our experiments. The explosion of the

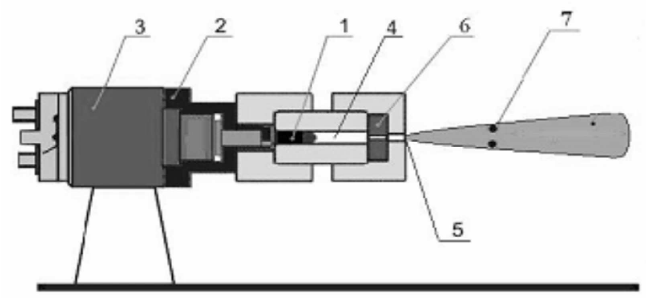

Fig. 1. PJ generator

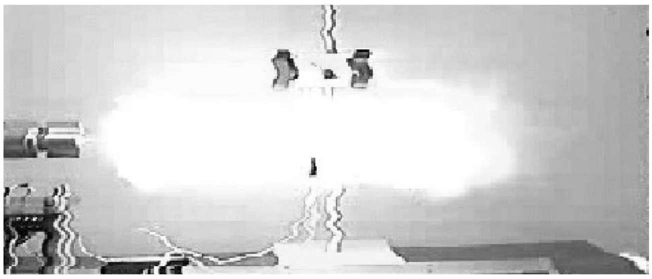

Fig. 2. Plasma jet

pyrocartridge takes place under the action of impact mechanism *2* controlled by electromagnet *3*. Due to the explosion in combustion chamber *4*, the temperature rapidly increases, which results in the formation of plasma from the particles of the substance filling the chamber. The shock wave and the gas expansion cause carrying out of plasma into the environment through nozzle *5* cut out in washer *6*. The generator outlet is constructed in the form of a Laval nozzle with the diameter of the minimum cross section and that of the outlet being equal to 2 mm and 3 mm, respectively. Measuring electrodes *7* are arranged immediately in PJ.

The PJ characteristics were determined by means of the probe measuring method [15, 16]. The arrangement of a probe in PJ required additional investigations aimed at choosing the optimal configuration of the measuring electrodes, their dimensions, and the ways of their fixing resistant to the influence of impact loads. For this purpose, we carried out the preliminary testing of electrodes of various configurations. It turned out that the best probe construction was that consisting of two parallel circular conductors 0.15 mm in diameter arranged at a distance of 6 mm from each other. Such a construction of the probe appeared to be the optimal as regards the resistance to the influence of impact loads. Moreover, it had the least deviation from the initial dimensions, which provided the reproducibility of the registered parameters. The electrodes were fixed in a rigid frame. The mechanical decoupling of the frame and the probe was fulfilled with the help of springs.

The formation of a conductive medium in the interelectrode gap of the probe results in the appearance of a current and the corresponding increase in the probe voltage. The signal from the probe is transmitted to the input of the analog-to-digital converter (ADC). The data from the ADC output are read by a computer and stored in the form of a data file, which allows one to carry out a further processing of the experimental results. The storage oscilloscope connected in parallel to the ADC gives a possibility to exercise the operative control in the process of measurements.

3. Investigation of the Parameters of Explosive Plasma Jets

Figure 2 shows PJ formed by an explosive generator. Visually, it represents a fire column of yellow color. The visible length of PJ amounts to 60—80 cm, while the diameter of its middle part is equal to 15—20 cm.

The average velocity of the PJ motion was determined by measuring the time, during which the jet covered a known distance. In our experiments, the time interval was measured in two ways. The first method used two break switches, one of them was arranged on the nozzle exit section, while the other one —- at a known distance (of about 1 mm) behind it. At the moment of the breaking, the first switch forms a pulse that activates the oscilloscope sweep, while the second switch applies voltage to the input of the vertical channel, which allows one to carry out the time reckoning of the PJ propagation. In the second measuring method, the switch was replaced with a piezosensor fixed on rubber shock dampers for the mechanical decoupling from metal parts of the carcass. The jet velocity measured by the first method was equal to 560 m/s, while the second method gave the value of 600 m/s. Thus, the dispersion of values of the jet velocity did not exceed 40 m/s. For the given construction of the nozzle and the energy of the pyrocartridge, we accept that the average velocity of the jet which passes to atmosphere approximates to 580 m/s.

Figure 3 represents the temporal evolution of the probe current (for various distances of a probe from the nozzle exit section). It's worth noting that the delay time between the beginning of the sweep and the appearance of a current is determined by the velocity of PJ in this region. One can see that the jet covers this distance during approximately 0.4 ms. This testifies that, at this

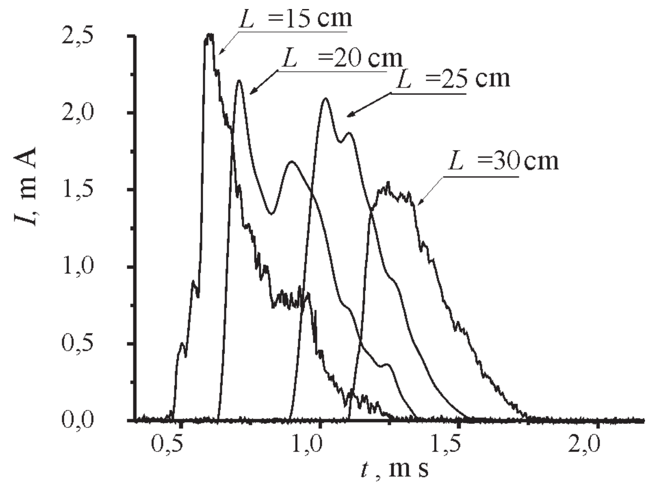

Fig. 3. Probe current at various distances from the nozzle exit section

region, the average velocity of PJ amounts to 273 m/s. Thus, with propagation of PJ, its velocity decreases. At a distance of 15 cm, the decrease of the velocity with respect to its initial value amounts to 307 m/s.

The presence of oscillations on the characteristic of the voltage across the interelectrode gap is associated, first of all, with the elastic character of the loading.

During the propagation of PJ in space, its parameters substantially change. With increase in the distance between the probe and the nozzle, the current amplitude decreases, while the pulse changes its form, which results from a decrease of the concentration of particles due to their recombination in the process of interaction with the environment. The change of the form of the current curves testifies to the existence of nonlinear processes in PJ determined by the development of Rayleigh—Taylor instability [15, 17, 18].

An inessential time overlap of the currents at distances of 15 and 30 cm proves that the length of the active region of PJ (the space domain whose conductivity differs from that of the environment) approximates to 15 cm.

The transverse displacement of the probe with respect to the PJ axis results in a change of the form of the current curves. The shift by 10 mm from the PJ center causes a decrease of the delay time of the probe signal, which allows one to assume that, in the plasma flow, there exist layers with different velocities lengthwise the jet which intensively exchange by particles. The experimental and theoretical investigations of explosive currents [15] give analogous results.

In our investigations, the minimal value of the resistance of the interelectrode gap amounted to 930 Ohm; the time interval, during which it did not exceed 1 kOhm, was a little higher than 30 μs. At the same time, the interval during which the resistance of the interelectrode gap of the probe amounted to 1.5 kOhm was equal to 95 μs.

The investigations demonstrate that the increase of the pyrocartridge energy and additional components introduced to its charge allow one to increase the PJ current in our experiments by 40—50 %.

The calculations show that, according to the obtained experimental data, the integral resistance of the jet does not exceed 1 Ohm. Surely, this value lies far from the conductivity of metals, but it still allows one to use PJs as radiative elements at time intervals of about 100 μs.

The concentration of the obtained plasma formations was estimated with the help of the recalculation of the conductivity using the technique [19] for plasma formations. The processing of the experimental data as regards the estimation of the particle concentration in the plasma column indicates that the maximal density of particles reaches 10^{13} cm^{-3}. The propagation of a jet in the atmosphere is accompanied by a decrease in its density. The decrease of the density over the whole active part of the jet formed under our conditions amounts to 0.6×10^{-12} cm^{-3}. The radial reduction of the jet concentration allows one to estimate the diameter of its active part at 10—12 mm.

4. Interaction of the Plasma Jet with the Field of a Spiral

In order to excite a surface wave in PJ having a linearly extensive structure, it is appropriate to use systems with distributed parameters, for example, spirals of different types. With their help, one excites antennas of different kinds [20, 21]. In this case, the diameter of the spiral D is consciously chosen to be lower than the wavelength λ of the signal ($D \approx \lambda/\pi$) exciting the spiral. Under this condition, the spiral is characterized with a large standing-wave factor, which results in the establishment of periodically interchanging maxima and minima of the field over the surface of the spiral wire. The corresponding values of the amplitudes are also established in the spiral volume. The form of the directional diagram of such a spiral is similar to that of a frame antenna, whose radiation maximum is directed at right angle to the spiral axis. Considering the propagation of PJ inside the spiral, to which a signal from the external generator is applied, one can mark out three principal stages of the development of the process which are indicated in Fig. 4.

On the first stage, PJ proceeds inside the spiral and reaches the position of the first maximum of the field amplitude. On the second one, the jet propagates inside the spiral without exceeding its bounds. The third stage starts from the moment when PJ goes beyond the spiral and propagates in free space.

The measured current of the probe is proportional to the concentration of charged particles in plasma. That's why one can consider that the change of the probe current reflects the regularity of the temporal behavior of the particle concentration. In this case, one should take into account that the plasma frequency also changes in time according to the equation

$$\omega_p\left(t\right) = \left(\frac{4\pi n\left(t\right) e^2}{m}\right)^{1/2}, \quad (1)$$

where $n\left(t\right)$ represents the law of the temporal variation of the particle concentration, e is the charge of a particle, and m is its mass.

The permittivity of PJ is connected with the plasma frequency and the operating frequency ω of the signal by the well-known relation [1]

$$\varepsilon\left(t\right) = 1 - \frac{\omega_p^2\left(t\right)}{\omega^2}. \quad (2)$$

From relations (1) and (2), one can see that, on the first stage, where the particle concentration in PJ is not high, plasma behaves as an insulator with respect to the operating frequency of the signal.

As plasma fills the internal volume of the spiral, there takes place a rapid redistribution of the current maxima at the expense of their interaction. In turn, this variation induces the radiation of the electromagnetic field, whose amplitude is proportional to the rate of change of the current, into the space.

It is known that a surface wave is excited at the plasma interface [22]. The enlargement of the geometrical length of PJ results correspondingly in the increase of the energy extracted from the spiral. Thus, on the second stage, there takes place the accumulation of the electric energy in the surface wave of PJ.

On the third stage, plasma goes beyond the spiral volume into free space, while the energy accumulated in the surface wave is radiated.

These processes can be represented with the help of a phenomenological model — the method of equivalent circuits. The equivalent circuit of the interaction between the spiral and PJ is depicted in Fig. 5.

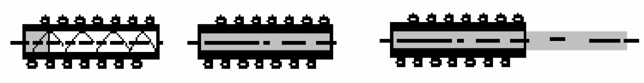

Fig. 4. Three successive stages of the interaction between PJ and the spiral field

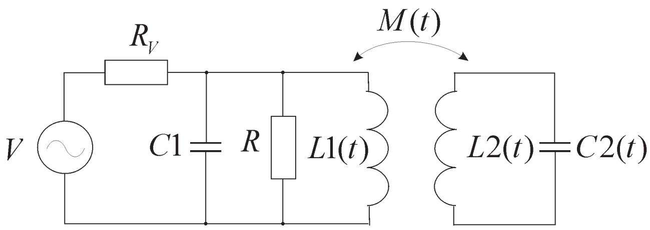

Fig. 5. Equivalent circuit of the interaction between the spiral and PJ

The signal from the external generator V characterized with the internal resistance R_V is applied to the parallel circuit $L1(t)C1$ formed by the inductance $L1(t)$ and the capacity $C1$ of the spiral. The oscillatory circuit with the time-dependent inductance $L2(t)$ and capacity $C2(t)$ is intended for the simulation of the processes of interaction between PJ and the field of the spiral. The $L2(t), C2(t)$ circuit is excited with the help of the inductive coupling $M(t)$ determined by the length and position of PJ. The losses in the circuits are taken into account by the introduction of the ohmic resistance R. The given model is constructed in the linear-parametrical approximation.

The result of the simulation carried out for an initial spiral current of 1 A indicates that the spiral current rapidly increases from the initial value $I_0 = 1$ A to 150 A.

5. Experimental Investigations of the Excitation of the Plasma Jet with an Electromagnetic Signal

In order to fulfill the experimental investigations of the excitation of PJ with the electromagnetic field, we created a test bench on the basis of the PJ generator. The jet formed with the generator propagates inside the spiral wound round the dielectric carcass. The diameter, pitch, and length of the wiring were equal to 50, 10, and 280 mm, respectively. The signal with a power of 5 W and a frequency in the range 360—520 MHz was supplied from the external generator to the spiral. In order to measure the amplitude of the electromagnetic field in space, we used shortened vibrators, whose signal

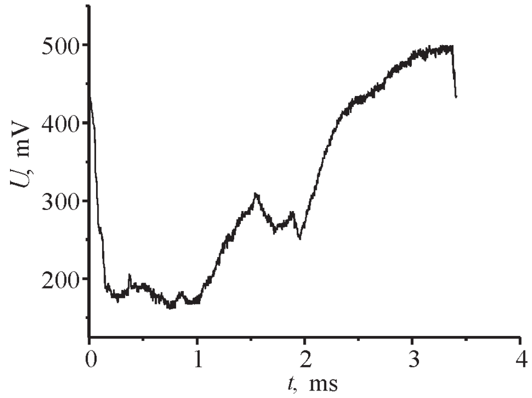

Fig. 6. Output signal of the detector measured as PJ propagates inside the spiral

was transmitted to the detector. The detector output was loaded with the resistance, whose voltage was supplied to the ADC. The discretization period of the ADC approximated to 3 μs. In the course of our investigations, the value of the load resistance of the detector changed in the range 1 kOhm — 1 MOhm. In a number of our experiments, we connected a capacitor 80—1000 pF in capacity in parallel to the load resistance of the detector, which allowed us to reduce the noise level when performing investigations. The construction of the test bench gave us a possibility to carry out measurements of the field distribution in space and in the spiral volume.

In our experiments, the receiving antenna was located at a distance of 30—150 cm from the spiral. The initial level of the signal at the detector output amounted to 30—500 mV depending on the location of the receiving antenna and its orientation. It's worth noting that the minimal signal strength at the detector output was observed in the case where the receiving antenna was arranged along the spiral axis, while the maximal value of the signal corresponded to the transverse location of the receiving antenna. If the receiving antenna was arranged at right angle to the PJ axis, we observed the influence of the jet on the level of the incoming signal. In particular, the level of the signal fixed on the load approximated to 19 V.

Figure 6 shows the output signal of the detector in the case where the jet propagates inside the spiral which is measured taking actions on the protection of the detector. The detector was loaded with a resistance of 1 kOhm, in parallel to which a capacitor 80—240 pF in capacity was connected. As the jet propagates inside the spiral, the output signal of the detector decreases, which can be considered as an indirect confirmation of the correctness of the accepted model of the interaction between PJ and the spiral.

A limited discretization time of the used ADC did not allow us to observe the processes, whose frequency spectrum exceeded 167 kHz. That's why, in Fig.6, one cannot see a short-time burst of the signal that, in some experiments, resulted in the breakdown of the detector. After the jet goes out of the spiral volume, the signal increases, which agrees with our prognosis.

Thus, the experimental results confirm the adequacy of the initial physical model.

6. Conclusions

The measurement of the parameters of the obtained PJ demonstrates that the charge of the explosive substance, whose energy approximated to 1 kJ, allows one to form PJ characterized with a density of 10^{12}—10^{13} cm^{-3} in free space. In this case, the active length of the jet (the region with a heightened conductivity) reaches 15 cm.

The experiments demonstrate the essential inhomogeneity of the velocity of particles in the cross section of the jet. The particle concentration in the jet is maximal along its axis (10^{13}) and decreases with increase in the radius of its cross section and in the course of time.

Investigating the processes that take place in the "spiral — plasma column" system, we mark out three stages corresponding to different positions of the jet in the spiral volume.

Performing experiments aimed at the investigation of the interaction between the internal field of the spiral and the plasma column, we registered a sharp increase of the field amplitude (by approximately 20 dB) within the limits of the directional diagram. Such an increase is conditioned by the parametric mechanism of interaction between the internal field of the spiral and plasma, which results in the redistribution of the electromagnetic energy accumulated in the spiral.

After the jet goes beyond the bounds of the spiral, the amplitude of the electromagnetic fields increases, which is conditioned by the radiation of the plasma column.

We have proposed a linearly parametrical model of interaction between PJ and the spiral that allows one to estimate the character of these processes.

The registration of the signals by receiving antennas shows a possibility of using a plasma jet as a radio-frequency antenna.

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ДОСЛІДЖЕННЯ ВЛАСТИВОСТЕЙ ВИБУХОВИХ ПЛАЗМОВИХ СТРУМЕНІВ ТА ЇХНЬОЇ ВЗАЄМОДІЇ З ЕЛЕКТРОМАГНІТНИМИ ХВИЛЯМИ

В.А. Сошенко, О.В. Ситнік, А.С. Тіщенко

Р е з ю м е

Наведено результати експериментальних досліджень вибухових плазмових струменів (ПС), сформованих у відкритому просторі. Показано можливість і вивчено умови випромінювання імпульсних електромагнітних сигналів плазмовими струменями. Наведено аналіз результатів експериментів з короткими й довгими ПС. Зафіксовано короткочасне зростання випроміненого сигналу під час проходження струменем поля спіралі. Запропоновано лінійно-параметричну модель взаємодії ПС зі збуджуючим електромагнітним сигналом.