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OPTICAL INSTRUMENTATION

On the Nature of Radiation of Blue and Green Jets in Laboratory Discharges Initiated by Runaway Electrons

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Abstract—Spectral and amplitude-temporal parameters of radiation from different regions of discharges initiated by runaway electrons have been studied. The pulse-periodic mode of discharge formation was used. It is shown that the color of a part of jets observed during laboratory discharges is determined by radiation of electrode metal vapors. It is found that blue mini jets from an electrode with a small radius of curvature appear in the cases of stainless steel and aluminum electrodes and are caused by emissions of atomic transitions of these metals. Green mini jets observed near copper electrodes are mainly caused by CuI atomic transitions mainly at wavelengths of 521.8 and 522 nm. It is confirmed that jets of different colors appear during formation of bright spots on electrodes, as well as sparks in the discharge.

Keywords: pulse-periodic discharge initiated by runaway electrons, blue and green mini jets in laboratory discharges in high-pressure air, nitrogen, and argon

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INTRODUCTION

Significant progress in the study of pulsed discharges in the Earth's atmosphere has been achieved recent years; in particular, radiation of jets of different colors with large glow areas were recorded (see, e.g., [1]). The nature of the radiation observed is studied in laboratory conditions. Thus, conditions for the appearance of sprites and blue jets were experimentally modeled in [2]. As a result, blue and red glow regions were recorded near a mylar film under microsecond discharges in dry low-pressure (0.02–100 torr) air. During the experiment, the film surface was first charged with a corona discharge of positive or negative polarity, and then a breakdown, which developed from the mylar film toward a grounded electrode, was observed during the discharge chamber evacuation. The pressure under which the breakdown was recorded depended on the film charge magnitude and, hence, on the electric field strength in the gap. No spectral studies were carried out in [2].

It is shown in [3, 4] that diffuse discharge regions of different colors in the form of jets are observed in discharges initiated by runaway electrons in air and nitrogen under high pressures. During the experiments, the setup, which consists of a discharge chamber and high-voltage pulse generator [4, 5], was used. Voltage pulses of positive or negative polarities with amplitudes of ~250 kV from the RADAN-220 generator were fed to a small-curvature-radius electrode made of 100-μm stainless steel foil through a short transmission line. A grounded flat electrode was located at 13 mm from the potential electrode. The voltage pulse length was ~2 ns under matched load and the voltage pulse front length in the transmission line was ~1 ns. The experiments [3, 4] were carried out in the single pulse mode at a discharge current amplitude of several kiloamperes. A runaway electron-preionized diffuse discharge (REP DD) was initiated in the gap, against which spark leaders were observed as the pressure increases, and spark channels, at further increase in the pressure [6]. The REP DD was formed due to generation of a supershort avalanche electron beam and X rays [6, 7]. Bright spots were seen on the small-curvature-radius electrode under pressure from 0.01 to 0.7 MPa. Spots appeared at the flat electrode when the gas pressure increased, as well as when the generator polarity changed from negative to positive.

As for pulses, diffuse jets of different colors were recorded in the gap against the REP DD glow. The jet color [3, 4] was visually the same as the color of radiation of sprites and blue jets in the upper atmospheric layers [1]. It was ascertained that red mini jets are formed in the region of decreased electric field near the flat electrode independently of the pulse generator polarity, and blue mini jets, in the region of increased electric field. These jets started from bright spots on the electrodes. Blue mini jets originated near both electrodes under a discharge between two knife elec-

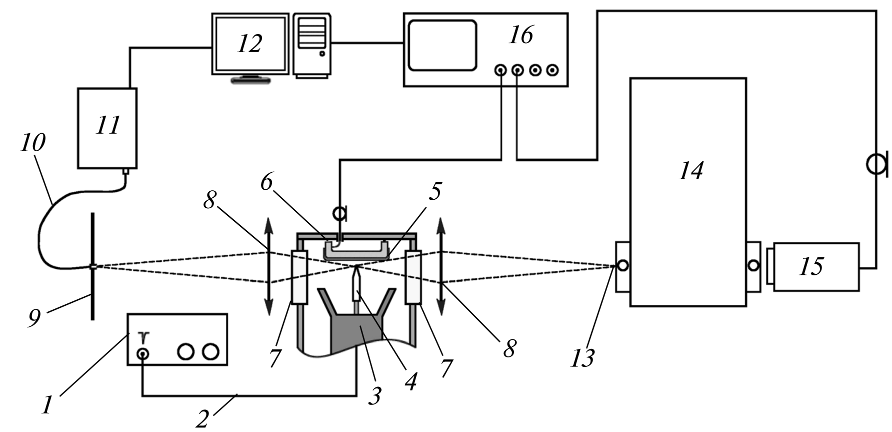

Fig. 1. Experimental setup: NPG-15/2000N generator (*1*), cable (*2*), insulator (*3*), cathode (*4*), anode (*5*), chip resistors of current shunt (*6*), side windows (*7*), lens (*8*), screen with a hole (∅ ≈ 0.46 mm) (*9*), optical fiber (*10*), spectrometer (*11*), computer (*12*), Hartman diaphragm (*13*), MDR-23 monochromator (*14*), PMT-100 (*15*), and TDS3034 oscillograph (*16*).

trodes in nitrogen. Formation of a red mini jet was observed in [4] in the center of the gap near the spark channel. In addition, it was shown that the radiation intensity of mini sprites and blue mini jets increases as the nitrogen pressure in the discharge chamber increases up to 0.4 MPa, and it decreases at a pressure of 0.7 MPa under the conditions of discharge contraction. However, spectral and amplitude-temporal radiation parameters were not studied in [3, 4] because of the unstable appearance of jets. Blue and red mini jets appeared at different points in the gap and started from different points on the electrodes. The shape and radiation intensity changed from pulse to pulse.

The aim of this work is the study of spectral and amplitude-temporal parameters of radiation of mini jets of different colors in laboratory discharges under high pressure to determine the nature of this radiation.

SETUP AND TECHNIQUES

The experiments were carried out in a setup which consisted of a high-voltage nanosecond pulse generator, a discharge chamber, and spectrometers (Fig. 1). Generator *1* formed voltage pulses of negative polarity with an amplitude of ~13 kV, full width at half maximum of 10 ns, and front length of 4 ns; the maximal discharge current was ~300 A. Voltage pulses were applied to cathode *4*, which is cone shaped and has a base diameter of 6 mm and radius of curvature of the apex of the cone of about 0.2 mm. This electrode shape was chosen to stabilize the point of appearance of bright spots on the cathode, as well as places anchoring the spark channel, which occurs at high pressures. The pulse repetition frequency was 60 Hz. Flat anode *5* 38 mm in diameter was located at 2 and 3 mm from the cathode. The cathode and anode were removable and made of different metals: copper, aluminum, and stainless steel. To record the discharge plasma emission spectrum from different zones in a plane that passed through the symmetry axis of the discharge gap, the discharge plasma was imaged with twofold magnification using lens *8* on a screen with a hole *9*. The screen with a hole could be shifted parallel to the plane that passed through the symmetry axis of the discharge gap and, thus, the discharge zone of interest was selected. Optical fiber *10* was located behind the screen; through which the radiation from the selected discharge zone was guided to spectrometer *11* (HR4000, Ocean Optics B.V., λ = 330–425 nm and EPP-2000C, Stellar-Net Inc., λ = 192–855 nm). Monochromator MDR-23 *14* and PMT-100 *15* were used for recording temporal parameters of the discharge plasma radiation. The discharge plasma was imaged with twofold magnification in the plane of Harman diaphragm *13* mounted near the entrance slit of the monochromator. A grating (1200 grooves/mm) was mounted in the monochromator, which provided for reciprocal linear dispersion of 13 Å/mm. Signals from a current shunt, consisting of chip resistors *6*, and the PMT were transmitted to oscillograph *16*. Signals from the spectrometer and the oscillograph were transmitted to computer *12*. The discharge glow was recorded with a Sony A100 mirror camera. The discharge chamber was pumped out with a forepump and then filled with nitrogen, Ar, and air (P = 30–760 torr).

EXPERIMENTAL RESULTS AND DISCUSSION

The study of a pulse-periodic discharges formed in the point–plane gap with inter-electrode space of 3 mm has shown that a REP DD is formed in nitrogen, air, and Ar at a pressure of 30, 50, and 100 torr when a high-voltage pulse is applied to the cathode with a small radius of curvature. The radiation of the second positive system of nitrogen is the highest in the case of REP DD in air and nitrogen [7–9].

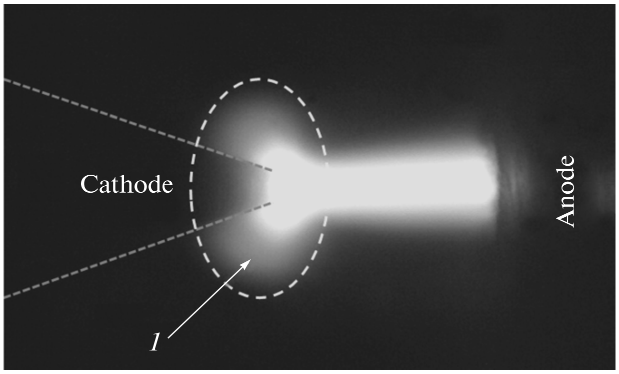

Fig. 2. Discharge in nitrogen under a pressure of 200 torr photographed for 60 pulses. Stainless steel cathode; interelectrode gap of 3 mm.

If electrodes were made of stainless steel, blue jets were observed near the small-curvature-radius cathode, like in [3, 4]. A discharge in nitrogen at a pressure of 200 torr is shown in Fig. 2. The region where blue jets were observed is marked by *1*; they started from bright spots on the stainless steel cathode. The discharge was photographed for 60 pulses in the pulse-periodic mode with a frequency of 60 Hz. Blue flares appeared near the stainless steel cathode beginning from a pressure of ~100 torr, and their brightness and frequency increased with the pressure. No clearly pronounced red mini jets were recorded on the flat anode and stainless steel cathode in the experiment, though some discharge regions were reddish.

Individual bright green jets appeared in the case of the copper cathode under pressures of 30 and 50 torr from bright points on the cathode surface, and blue jets, in the case of the aluminum cathode. The green and blue jets appeared mainly near the cathode tip as the pressure increased. No clearly pronounced red jets were observed as well in the cases of Cu and Al electrodes.

We believe that the formation of green (Cu cathode) and blue (Al and stainless steel cathodes) flares is caused by the explosion of microinhomogeneities on the cathode surface and electroerosion of a metal in the conditions considered; as a result, metal vapors are formed and scatter in the ambient space. The glow region reduces as the pressure increases. This confirms that the glow region size is determined by the distance to which metal vapors fly during a discharge.

The emission spectra from the center of the discharge channel and a zone near the tips of the Al cathode (discharge in nitrogen under a pressure of 100 torr) and a stainless steel cathode (discharge in air under a pressure of 200 torr) are shown in Figs. 3 and 4, respectively. The emission spectrum from the Al cathode was measured with HR4000 with a high spectral resolution, and from the stainless steel cathode, with EPP-2000C. The radiation of the second positive system of nitrogen N_2(C–B) is evidently of the highest intensity in the emission spectrum from the gap center in the wavelength range under study. In the case of contracted discharge in air (see Fig. 4), the continuum is recorded almost throughout the whole range under

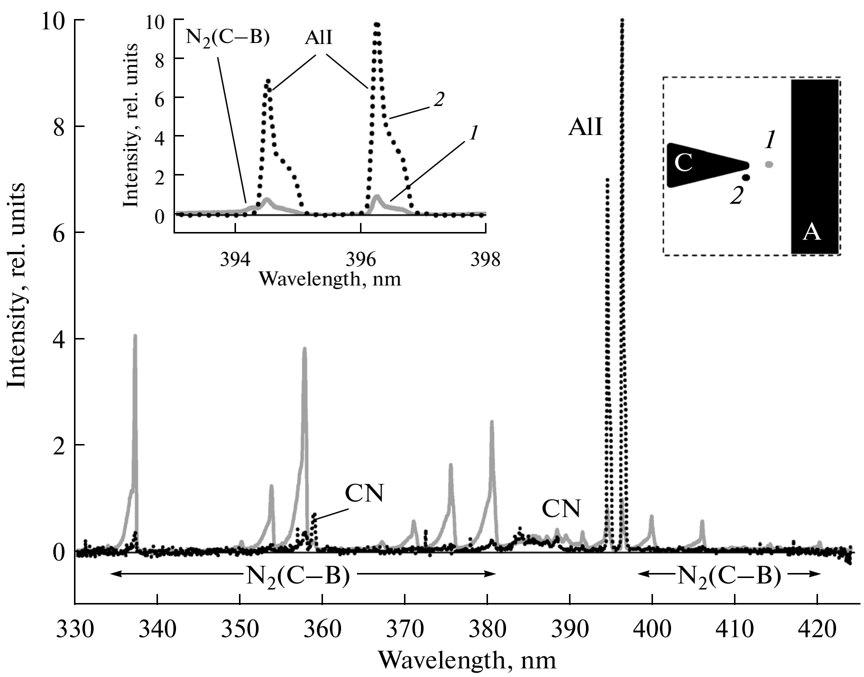

Fig. 3. Emission spectra discharge plasma in nitrogen under a pressure of 100 torr. Aluminum electrodes; interelectrode gap of 2 mm.

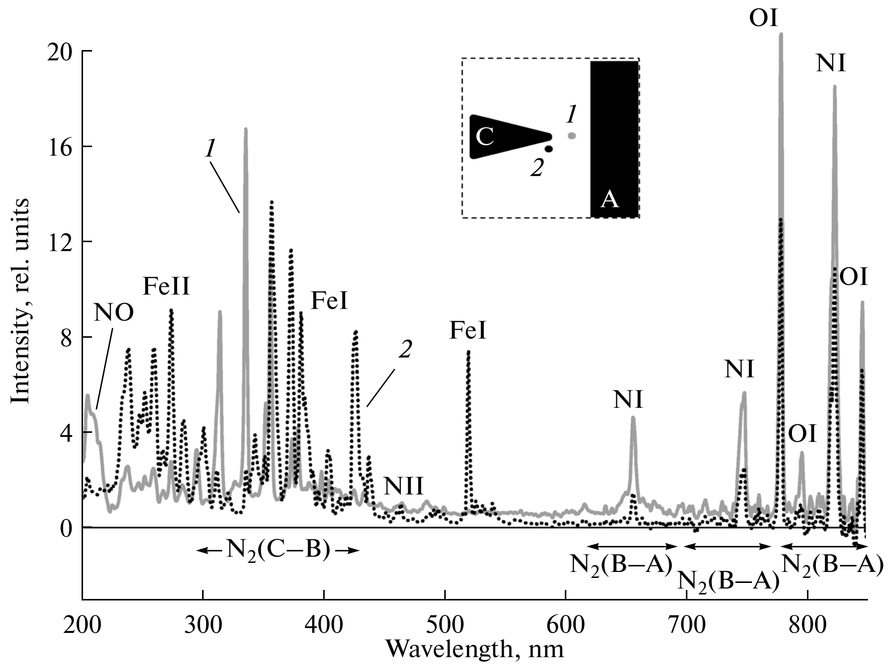

Fig. 4. Emission spectra discharge plasma in air under a pressure of 200 torr. Stainless steel electrodes; interelectrode gap of 3 mm.

study, NI atom lines and weak lines of nitrogen ions NII, as well as lines of oxygen atoms OI and high-intensity NO bands. Near the tip (zone *2*), radiation of AlI and FeI atoms and FeII ions prevails, i.e., of atoms and ions of the cathode metal. Strong lines of Al atoms (AlI) with wavelengths of 394.4 and 396.15 nm are seen in Fig. 3 (zone *2*); they have common upper level $3s^24s^2S_{1/2}$ (3.14 eV) and lower (ground) levels $3s^23p^2P^0_{1/2}$ (0 eV) and $3s^23p^2P^0_{3/2}$ (0.014 eV), respectively. The radiation wavelengths at different transitions of metal atoms were identified with the use of data from [10].

Only general profiles that envelop many iron atoms and ion lines are seen in Fig. 4 (zone *2*). According to [10], about 12 500 lines of iron atoms and ions are numbered in the wavelength range 200–600 nm. The analysis performed has shown that mainly FeII lines radiate in the 200–300 nm wavelength range, and FeI lines, in the 300–600 nm range. Thus, e.g., 135 FeI lines are accumulated in the 420–430 nm region, which imparts a blue color to mini jets, while only the spectrum envelope is seen in Fig. 4.

It should be noted that the metal atom and ion line intensity dependence on the gas pressure is nonmonotonic near the tip and attains its maximum at a pressure of 100–200 torr. The nonmonotonic character is caused, on the one hand, by an increase in the discharge current density and, hence, density of metal vapors formed during microtip explosions and electroerosion with pressure, and, on the other hand, a decrease in the distance to which the metal vapors scatter with an increase in the pressure.

Figure 5 shows the time variations in the nitrogen molecule radiation at a wavelength of 380.5 nm and Al atom radiation at a wavelength of 396.15 nm, as well as the discharge current in nitrogen under a pressure of 200 torr. The spiking structure of a current pulse is caused by a mismatch between the impedance of load, transmitting cable, and generator, due to which a current pulse produced by the generator was multiply reflected. Therefore, the total duration of the discharge current was ~1.5 μs. Figure 5 shows that the radiation pulses of the nitrogen molecule system are short (oscillogram *1*), which is caused by a rapid decrease in the electron temperature in REP DD [7]. The radiation pulse length is also limited by the discharge contraction [8, 9]. The Al atom radiation intensity has two peaks. The second, more gentle peak, is attained in 0.7 μs after the gas breakdown. The total Al atom radiation pulse length exceeds the discharge current length.

CONCLUSIONS

We have shown that formation of mini jets of different colors against a REP DD are often caused by the excitation of electrode metal vapors which arrive at the gap after microtip explosions. Mini jets are blue in the case of stainless steel and aluminum electrodes and green in the case of copper electrodes. The color of mini jets observed is caused by radiation mainly from FeI, AlI, and CuI transitions. The study performed

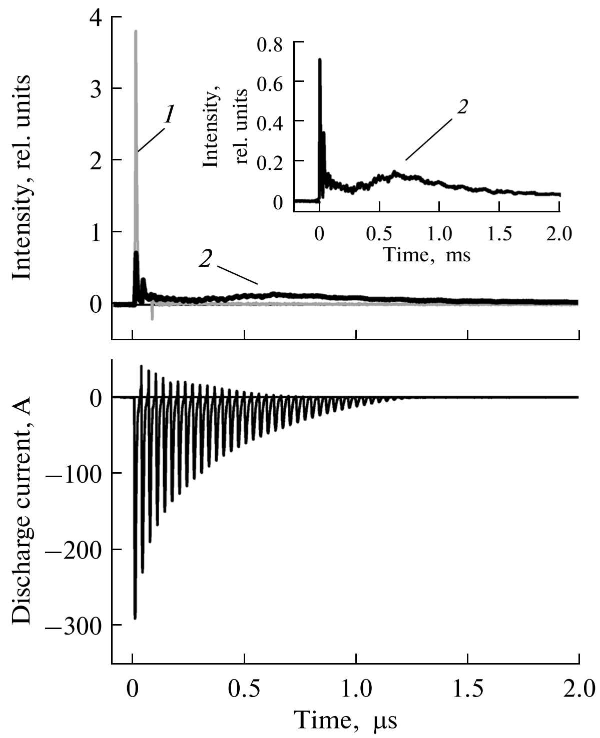

Fig. 5. Oscillograms of radiation pulses and discharge current: pulse of nitrogen molecule radiation at a wavelength of 380.5 nm (*1*); pulse of Al atom radiation at a wavelength of 396.15 nm (*2*).

also confirms that high-intensity radiation of the second N_2(C–B) and first N_2(B–X) positive systems of nitrogen is observed during diffuse discharges in air (see Figs. 3 and 4). Radiation of these systems is recorded from sprites and blue jets of atmospheric discharges [1, 11].

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