Non-Self-Sustained Discharge in Nitrogen with a Condensed Dispersed Phase

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Abstract—A non-self-sustained discharge in nitrogen with a condensed dispersed phase is studied experimentally for the first time under atmospheric pressure at room temperature. It is shown that macroparticles strongly affect the current–voltage characteristics as well as the stability of the discharge process. A numerical simulation of dust particle charging in nitrogen is carried out at room temperature and cryogenic temperatures under continuous medium conditions. It is shown that a considerable charge is accumulated at macroparticles in the nitrogen beam plasma. As the gas temperature decreases, the charge of macroparticles in nitrogen increases, while in argon their charge decreases. For this reason, the Coulomb interaction parameter for dust particles in nitrogen increases strongly upon a transition from room to cryogenic temperature, while in argon this parameter decreases. It is also shown that the characteristic time of dust particle charging is shorter than 1 ms for a beam current density of 90 $\mu$A/cm$^2$, while the neutralization of the charge takes milliseconds. Possible mechanisms of the influence of the dust component on the characteristics of non-self-sustained discharge are considered.

1. INTRODUCTION

The interest in plasmas with a condensed dispersed phase (CDP) has increased during the last decade in connection with considerable advances in microtechnology and the progress in obtaining new materials [1, 2]. This interest is also due to the fact that such plasmas are the simplest real objects for studying self-organization processes which are of fundamental importance. Such a medium makes it possible to carry out experiments on convenient time and space scales and practically with the naked eye. The study of a non-self-sustained discharge in helium with a CDP revealed [3] that in a constant electric field, the current density in the discharge decreases upon an increase in the concentration of dust particles. The rate of the current density drop increases with the field. The theoretical model of a non-self-sustained discharge with a CDP constructed in [3] was based on the approximation of the orbital motion of electrons. The necessary condition for such an approximation to be applicable is that the molecular mode of electron motion is realized in the vicinity of a dust particle, where the quasi-neutrality of the plasma is violated. Under atmospheric pressure, the opposite case is realized in molecular gases, where the regime of a continuous medium takes place for the transport of charged particles. In this case, the description of the charging of macroparticles in the plasma of a non-self-sustained discharge is simplified since the joint solution of Boltzmann’s equation for the electron energy distribution function (EDF) plus the continuity equations for charged particles and Poisson’s equation for the electric field is not required. Consequently, it becomes possible to construct a consistent and comprehensive mathematical model of dust particle charging, which has been verified on other objects. For this reason, the study of a non-self-sustained discharge in molecular gases with a CDP is of considerable interest.

A non-self-sustained discharge in molecular gases is widely used for pumping CO$_2$, CO, and other high-power gas lasers. In such lasers, the erosion of electrodes or the polymerization of particles of the original gas or radicals formed in the discharge (e.g., the “laser snow” effect in the active medium of the XeCl laser [4]) leads to the formation of macroscopic particles in the working volume. Such particles can be responsible for a change in the characteristics of the discharge process and in the operation of the device proper (see [5] and the literature cited therein). For example, aerosol particles may lower the discharge stability. It was noted in [5] that the presence of dust particles in a high-pressure CO$_2$ laser and in excimer lasers correlated with instabilities such as discharge contraction or multiple streamers.

The present work is devoted to experimental and theoretical analyses of the effect of the dust component on the characteristics of a non-self-sustained discharge in nitrogen under atmospheric pressure, which is controlled by a fast electron beam.
2. EXPERIMENT

The experiments were carried out in the plasma of a pulsed non-self-sustained discharge in nitrogen on the setup described in [3]. We used nitrogen with an impurity concentration below 0.005%. As in [3], the dust component was in the form of carbon glass balls 24 ± 5 μm in diameter. The experimental conditions were chosen so that, first, a comparison with the results of similar experiments in helium was possible, and second, the widest possible range of electric fields in the nitrogen plasma was covered. A non-self-sustained discharge was initiated under atmospheric pressure. The current density in the fast electron beam with an energy of 125 keV was 90 μA/cm² for various concentrations of macroparticles: (a) $U = 780$ V, $n_d = 0$ (curve 1), $3.1 \times 10^3$ (curve 2), and $4.8 \times 10^5$ cm⁻³ (curve 3); (b) $U = 2.1$ kV, $n_d = 0$ (curve 1), $1.4 \times 10^4$ (curve 2), and $2.8 \times 10^5$ cm⁻³ (curve 3).

The current of a non-self-sustained discharge in nitrogen at $j_b = 90$ μA/cm² for various concentrations of macroparticles: (a) $U = 780$ V, $n_d = 0$ (curve 1), $3.1 \times 10^3$ (curve 2), and $4.8 \times 10^5$ cm⁻³ (curve 3); (b) $U = 2.1$ kV, $n_d = 0$ (curve 1), $1.4 \times 10^4$ (curve 2), and $2.8 \times 10^5$ cm⁻³ (curve 3).

The working range of voltages was from 2 to 3 kV for a stable discharge time of at least 150 μs.

Typical oscillograms for the discharge current are shown in Figs. 1a (helium) and 1b (nitrogen). For discharge voltages up to 800 V, the discharge current in helium virtually does not change in a certain time interval (400–1000 μs after the initiation of the discharge, the current can only increase by 10% for zero or low concentrations $n_d$ of microparticles and decrease by the same value for $n_d > 10^5$ cm⁻³). In contrast to experiments with helium, the quasi-stationary mode of the discharge in nitrogen was not observed under our conditions (the discharge current in Fig. 1b increases monotonically with time). For this reason, we compared the values of discharge current at 150 μs, when we can assume that the formation of the cathode layer is completed and the current becomes a linear function of time, and also at 400 μs.

Figure 2 shows the discharge current in nitrogen and helium, reduced to the values of a non-self-sustained discharge in the absence of dust particles, as a function of the concentration of dust particles 150 and 400 μs.

The current $I_d$ of a non-self-sustained discharge in nitrogen at $j_b = 90$ μA/cm² for various concentrations of macroparticles: (a) $U = 780$ V, $n_d = 0$ (curve 1), $3.1 \times 10^3$ (curve 2), and $4.8 \times 10^5$ cm⁻³ (curve 3); (b) $U = 2.1$ kV, $n_d = 0$ (curve 1), $1.4 \times 10^4$ (curve 2), and $2.8 \times 10^5$ cm⁻³ (curve 3).