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Equilibrium and non-equilibrium gas discharges sustained by powerful radiation of the terahertz frequency range in noble gases

© A.V. Sidorov, A.P. Veselov, A.V. Vodopyanov, M.Yu. Glyavin, Yu.K. Kalynov, A.G. Luchinin

Federal Research Center A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia
E-mail: alexsv@ipfran.ru

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The results of a study of the spatial dynamics of a discharge in pure noble gases and their mixtures (helium with the addition of argon) in a wide range of gas pressures (0.2–1.5 bar) are presented. The studies were carried out for several frequencies of heating radiation (250, 263 GHz and 1 THz) in a wide range of power densities in the focal spot (from fractions of a kW/cm^2 to several MW/cm^2). At relatively low power densities, the discharge propagation had an equilibrium character, while at high power densities it was nonequilibrium. Various mechanisms of propagation of nonequilibrium and equilibrium discharges are discussed.

Keywords: Terahertz radiation, gas discharge, discharge propagation.

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The processes of gas discharge generation and dynamics in focused beams of electromagnetic radiation have been investigated in detail in the MHF- [1–5] andIR- [6] ranges. The terahertz (THz) frequency range, which lies between them, has become available to gas discharge physics researchers relatively recently due to progress in the development of powerful sources in this frequency range: free-electron lasers and gyrotrons [7–10].

The study of gas discharge in THz- frequency range is of interest also because it can act as an intense source of UV-radiation [11].

The present work is devoted to the study of the spatial dynamics of a discharge maintained in inert gases in focused THz-wave beams of the frequency range. Already in the first experiments on creation of laser spark [12] an interesting phenomenon related to the discharge propagation along the heating radiation or towards it was discovered. Subsequently, it was shown that the discharge propagation has much in common with the combustion process [6]. This phenomenon has also been extensively investigated in the microwave-range [1–5], primarily in atmospheric pressure air [5], although there have also been several works on microwave -discharge propagation in inert gases [1,13,14]. It should be noted that interest in the propagation of microwave-discharge in inert gases has not waned so far [15,16].

In the present work, studies of THz-frequency range discharge propagation in various noble gases were carried out for several frequencies of heating radiation (250, 263 GHz, and 1 THz) over a wide range of pressures (0.2–1.5 bar). Note that in this case the frequency of collisions of electrons with atoms could be both larger than the circular frequency of the field and smaller. For example, for argon (which was used in the bulk of the experiments), the collision frequency is compared to the circular field frequency for 250 GHz at a pressure of 0.4 bar. In the case of microwave-discharges at such pressures, the collision frequency is usually substantially greater than the circular field frequency.

The sources of electromagnetic radiation were various gyrotrons differing both in the maximum possible power in the pulse and in the frequency of electromagnetic radiation.

The principle scheme of the experimental setups was practically the same in all cases, so we will describe it on one specific example. Fig. 1 shows a schematic of the experimental setup, in which a pulsed 250 GHz-gyrotron (pulse duration up to 40 μs, maximum power 250 kW) acted as a radiation source. The radiation from the gyrotron was directed into an evacuated vacuum discharge chamber using a two- or single-mirror (as in this case) quasi-optical system. There, it was focused into a spot with a diameter at the level of two-three wavelengths, which for a 250 GHz gyrotron provided a maximum radiation intensity of 3.5 MW/cm^2. For

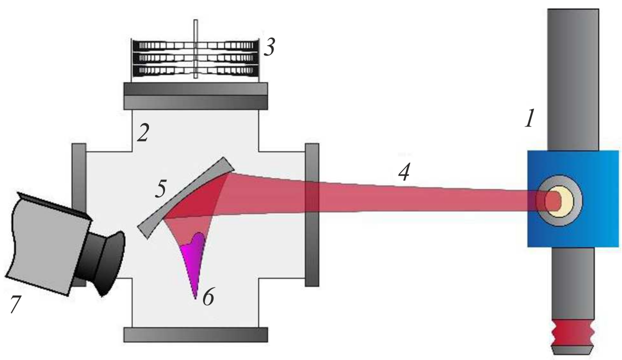

Figure 1. Schematic diagram of the experimental setup. *1* — gyrotron, *2* — vacuum discharge chamber, *3* — turbomolecular pump, *4* — THz-beam, *5* — focusing mirror, *6* — beam focus/discharge, *7* — Nanogate-24 chamber.

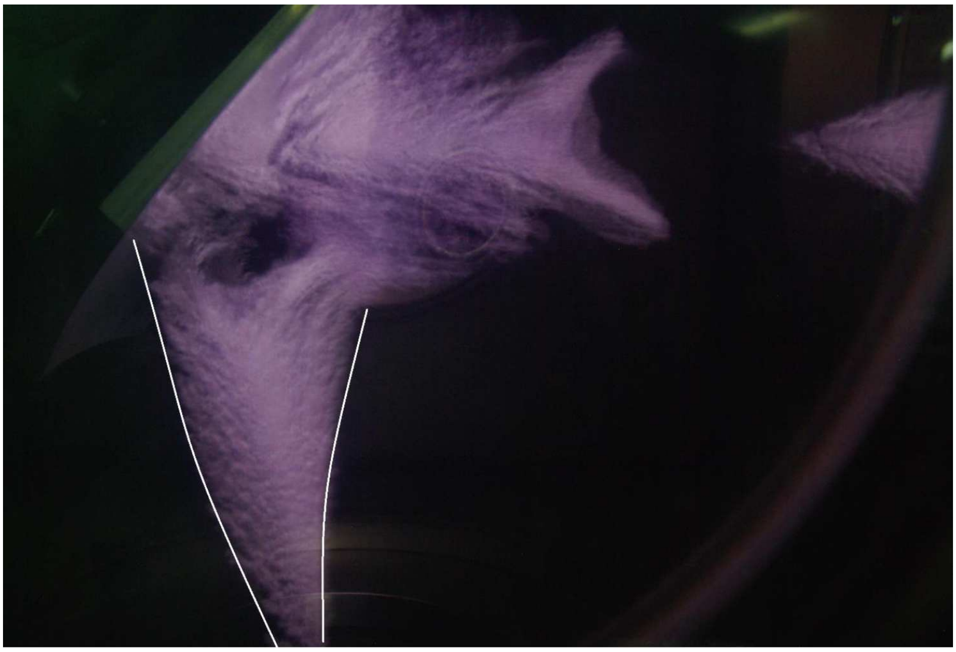

Figure 2. Photograph of the discharge in argon. Heating radiation frequency 250 GHz, gas pressure 50 Torr. The electromagnetic radiation propagates from right to left to the focusing mirror and then from top to bottom. Light lines schematically show the boundaries of the focused beam.

gyrotrons with maximum power in a kilowatt-level pulse (263 GHz, 1 THz), the maximum emission intensity was 15 and 250 kW/cm ^{2}, respectively.

The vacuum discharge chamber was pre-pumped to pressures at the level of 10^{-5}–10^{-6} Torr and then filled with working gas (argon, krypton, helium-argon mixture). A high-voltage spark discharge ignited near the focal spot of the heating electromagnetic radiation was used to initiate the discharge in cases, where the intensity of electromagnetic radiation was insufficient for independent breakdown (263 GHz- and 1THz-gyrotrons).

The discharge luminescence was investigated using a Pentax K10D camera (time integral photographs), a 60 fps video camera (for low discharge propagation velocities on the order of 100 cm/s), and a Nanogate -24 camera with slow shutter speeds (from 20 ns and up). For 20 ns the discharge has practically no time to displace (even at a velocity of 10^6 cm/s the displacement is less than 1 mm at characteristic distances of a few centimeters or even tens of centimeters), and such a photo can be considered practically instantaneous. By taking photos with different delays relative to the time of discharge ignition, it is possible to trace the temporal pattern of discharge propagation and measure its velocity. In those cases where the experimental conditions did not allow the use of a camera with a slow shutter speed, time-integral photographs of the discharge produced by gyrotron radiation with different pulse durations were used. At different pulse durations, the distance over which the discharge has had time to propagate varies, which makes it possible to estimate the average propagation velocity of the discharge.

In all experiments, the discharge appeared at the focus of electromagnetic radiation and propagated towards it. The behavior of the discharges supported by 250 GHz and 1 THz radiation was qualitatively the same, the same as in the case of the discharge supported by 670 GHz [17] radiation. The discharge luminescence had a strongly inhomogeneous character, which seems to indicate that it repeated the structure of the electric field strength, not necessarily vacuum (see the discharge photograph in Fig. 2). This indicates the field ionization of the gas and, consequently, the non-equilibrium character of the discharge. The discharge propagation velocity significantly exceeded the speed of sound and was at 10^5 cm/s (1 THz) and 10^6 cm/s (250 GHz). At the same time, as the pressure decreased from 1.5 to 0.2 bar, the discharge propagation velocity increased in both cases.

The only difference is that the discharge supported by radiation with a frequency of 250 GHz, initially propagates in the ultra-piercing fields (relative to the independent breakdown of cold gas), and then when travelling along the expanding beam of electromagnetic radiation falls into the region of pre-piercing fields, while the discharge supported by radiation with a frequency of 1 THz, being initiated, initially propagates in the pre-piercing fields.

The propagation of non-equilibrium THz-discharge in pre-fields, as in the case of microwave-discharge, is now attributed to UV-emission from -behind the discharge front [13]. This radiation ionizes the gas ahead of the

Figure 3. Photograph of the discharge in krypton. Heating radiation frequency 263 GHz, gas pressure 0.3 bar. The electromagnetic radiation propagates from left to right to the focusing mirror and then from top to bottom.

discharge front, resulting in a substantial fraction of the electromagnetic radiation being absorbed in this ionized gas, thereby heating the gas ahead of the discharge front. As a result of gas heating, the number of excited atoms increases, which lowers the breakdown threshold, since effective ionization from the excited state takes place at substantially lower electric field strengths than ionization from the ground state. The rate of discharge propagation in this case is determined by the rate of gas heating, and hence increases with the increase of electromagnetic radiation intensity and decrease of gas density.

In the case of a discharge supported by 263 GHz radiation (with significantly lower electromagnetic intensity), the pattern of discharge propagation is qualitatively different. The discharge luminescence (Fig. 3) no longer repeats the structure of the electric field, but repeats the gas temperature distribution. This means that ionization is thermal in nature, which corresponds to the equilibrium character of discharge propagation. The discharge propagation velocity, measured using a video camera with a frame repetition rate of 60 fps, was much lower than the speed of sound and did not exceed 100 cm/s, decreasing with increasing gas pressure.

As for the propagation mechanism, it now appears that the heating of the gas in front of the discharge front followed by its thermal ionization can be carried out both by the hot gas behind the discharge front (slow combustion [6]) due to thermal conduction and by absorption of electromagnetic radiation in front of the discharge front in the halo created by UV-radiation from -behind the discharge front [5]. At present, the first option seems to be more realistic, since in the case of the photo-ionization [5] mechanism, the characteristic propagation velocities of the equilibrium discharge are usually higher (at the level of 10^3 cm/s), as well as the intensity of the heating electromagnetic radiation. Nevertheless, the question about the specific mechanism of equilibrium discharge propagation in these experiments is still open.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by 123