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Experiments on creation and maintenance of plasma in focused gyrotron radiation beam with frequency 1 THz

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The first results of the study of the conditions of discharge generation in a focused beam of electromagnetic radiation of a gyrotron with a frequency of 1 THz are presented. The pressure breakdown limits of the working gas (argon) were determined (0.15−1.75 bar). The experimental results obtained correlate well with the calculations carried out earlier. The spatial dynamics of the discharge was investigated, and the propagation velocity of the discharge front as a function of gas pressure was measured. Assumptions are made about the mechanism of discharge propagation.

Keywords: terahertz radiation, gas discharge, discharge propagation.

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The study of the processes of plasma interaction with powerful radiation of the terahertz (THz) frequency range has become possible relatively recently due to progress in the creation of radiation sources in this range: gyrotrons and free electron lasers [1–4]. The study of gas discharge in the THz frequency range is of interest both from the point of view of basic science and possible applications. The dense plasma of a THz discharge created in an inhomogeneous gas flow can be used as a point-like source of ultraviolet radiation up to the extreme ultraviolet (EUV), since the plasma density $10^{15}–3 \cdot 10^{17}\,\mathrm{cm}^{-3}$ characteristic of this type of discharge is optimal from the point of view of the efficiency of EUV radiation [5]. This idea was experimentally confirmed in the work [6], where it was shown, among other things, that in order to increase the yield of EUV radiation, it is necessary to move to higher frequencies of heating radiation (up to 1−3 THz). The transition from traditional gyrotrons to so-called large orbit gyrotrons (LOGs) [7] is assumed to be promising.

Back in 2008, the IAP RAS created a LOG that provides stable generation at frequencies of 0.55 and 0.68 THz at the second cyclotron harmonic, as well as at frequencies of 0.87 and 1.0 THz at the third harmonic in pulses of 8 μs duration with pulse repetition rate up to 0.1 Hz [7]. Operating at a frequency of 0.55 THz, this LOG was successfully used in experiments to produce an inert gas discharge in a focused wave beam with a power of 1 kW [8]. At a frequency of 1 THz, the maximum radiated power was 400 W. As shown by [9] calculations based on the model [10], such a value of the pulse radiation power with frequency 1 THz and duration 8 μs is not sufficient for both independent and initiated breakdown of heavy inert gases (primarily argon). In the framework of modification of this LOG, due to the use of a resonator with a reduced diffraction goodness and improved mode selectivity, it was possible to increase the maximum power of radiation up to 1.3 kW [11]. This level of radiation power, according to calculations [9], is sufficient to realize the initiated breakdown of argon in a relatively wide range of pressures. The results of the first experiments on the creation and maintenance of plasma in argon in a focused beam of gyrotron electromagnetic radiation with a frequency of 1 THz are presented in this paper.

The experimental setup was the following. The quasi-optical transducer built into the LOG transforms the gyrotron radiation into a weakly diverging quasi-gaussian wave beam. Through a Teflon window 4 mm thick THz radiation is transported into the discharge chamber, the dimensions of which significantly exceed the diameter of the wave beam focused by a specially designed system of two mirrors in the center of the chamber (Fig. 1). This two-mirror system provided focusing of radiation in the center of the discharge chamber into a spot with a diameter at the level of 5 wavelengths, which corresponded to an RMS field strength of 5 kV/cm at the maximum gyrotron power of 1.3 kW. For additional focusing of radiation into a spot with a size close to the diffraction limit, a short-focus ($f = 0.9$ mm) parabolic mirror was placed in the center of the discharge chamber (the photo is shown in the inset to Fig. 1). By means of this mirror it was possible to achieve focusing of the electromagnetic wave beam into a spot with a diameter close to 2.5λ, which made it possible to increase the RMS value of the field strength in the focal spot to 10 kV/cm.

The vacuum discharge chamber was pre-pumped to forevacuum and then filled with working gas (argon) to

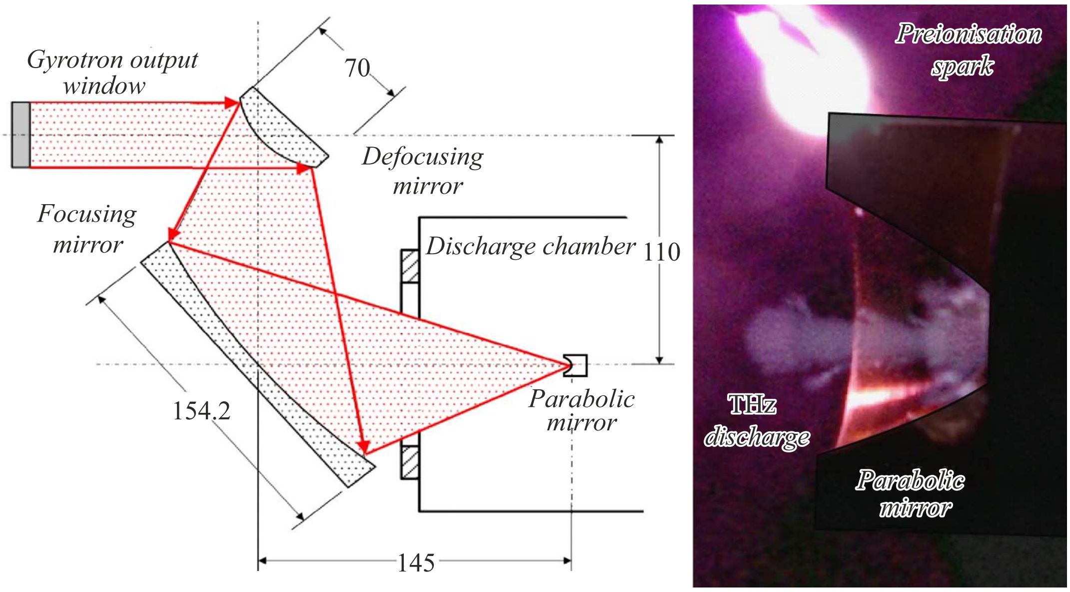

Figure 1. Diagram of the experimental setup. The inset — is a photograph of a discharge in argon for a gas pressure of 0.25 bar.

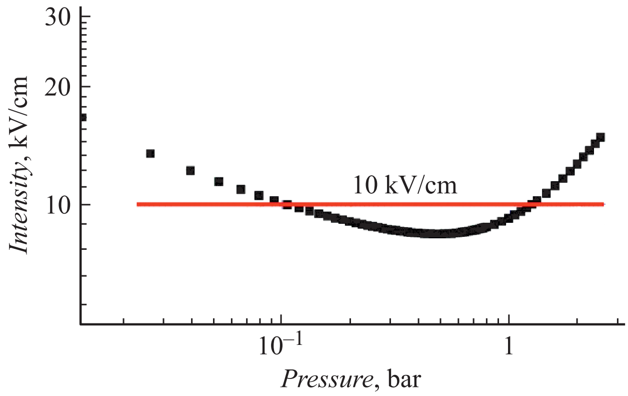

Figure 2. The theoretically calculated dependence of the strength of the breakdown fields on the gas pressure (argon), taken from the work [9]. Electromagnetic frequency 1 THz, pulse duration 8 μs, pre-ionization. The horizontal line marks the field strength in the focal region, maximally achievable in the experiment.

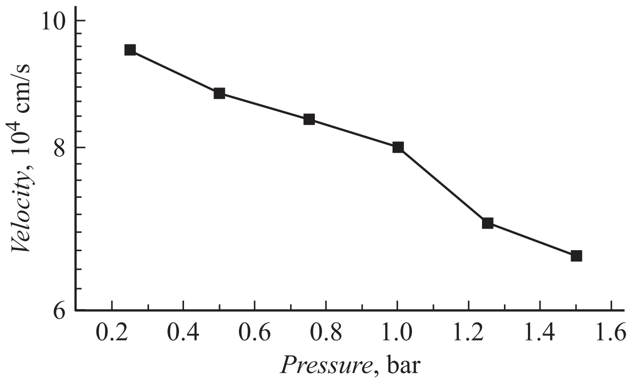

Figure 3. Dependence of discharge propagation velocity on gas pressure (argon).

the required pressure value. A spark discharge was used to initiate the breakdown. The presence of gas breakdown by gyrotron radiation was detected both visually and using a photomultiplier tube. The discharge originated in the focus region of the electromagnetic radiation and then propagated toward the heating radiation (see insert in Fig. 1). The argon gas pressure breakdown limits for a fixed field strength of 10 kV/cm were 0.15 and 1.75 bar. Fig. 2 shows the calculated breakdown curve for argon from the paper [9] for conditions corresponding to the experiment. It can be seen from the above figure that the pressure breakdown boundaries determined from the calculated breakdown curve are in good agreement with the experimental data.

As mentioned above, having appeared at the focus of the electromagnetic wave beam, the discharge propagated towards the heating radiation. The discharge propagation velocity was estimated from integral photographs of the discharge for different gyrotron pulse durations, other conditions being equal (power in the pulse, gas pressure). An example of a time-integral photograph of the discharge in the visible range for argon pressure of 0.25 bar is shown in the inset to Fig. 1. The discharge propagation velocity was calculated as follows. During the experiment, both pressure and power of the gyrotron were fixed, only the pulse duration of the heating radiation was changed. During the pulse time $\tau_1 = 8\,\mu$s the discharge according to the time integral picture spread to the distance L_1, while during the shorter pulse time $\tau_2 = 4\,\mu$s the discharge had time to spread only to L_2. Then the discharge propagation velocity was defined as $(L_1 - L_2)/(\tau_1 - \tau_2)$. The rate was determined by averaging over several bit realizations. The statistical error was no more than 10%. This measurement method allowed us to get rid of the uncertainty in finding the discharge ignition time, which could be different for different pressures. It should be noted that the velocity calculated in this way practically did not differ from the values L_1/τ_1 and L_2/τ_2. That indicates that the discharge was ignited practically simultaneously with the arrival of the electromagnetic radiation pulse (which was independently confirmed by the signal from the photomultiplier tube), and that the discharge propagation velocity along the entire trace (the entire length of the beam axis) was virtually constant. This is due to the fact that the discharge did not run away further than the waist (on the order of 1 cm) of the focusing mirror of the two-mirror system shown in Fig. 1, i.e., the value of the electric field strength along the discharge propagation path did not practically change, except for a small area of the discharge origin (of the order of 1 mm) at the focus of the short-focus paraboloid. At the same time, the field value on the propagation path was less than the breakdown value. A similar pattern was observed earlier [8].

The dependence of the discharge propagation velocity in argon on the gas pressure is shown in Fig. 3. It can be seen that the velocity exceeds the speed of sound ($3 \cdot 10^4$ cm/s for 1 bar argon) and decreases with increasing gas pressure. The discharge luminescence is inhomogeneous, which seems to be due to the fact that it repeats the structure of the electric field distribution. The propagation of THz discharge in subcritical field is now attributed, as in the case of microwave-discharge in inert gases [12,13], to the key role of ultraviolet radiation from-behind the discharge front. It leads to an increase in the number of excited atoms in front of the discharge front, thereby reducing the breakdown threshold, since effective ionization from the excited state is carried out at substantially lower electric field strengths than ionization from the ground state. The discharge propagation velocity is determined by the free path length of ultraviolet radiation, which grows with decreasing gas density.

Similar results have been obtained previously for emission frequencies of 28 [14], 75 [15], 250, 550, and 670 GHz. In the above-mentioned works it was also noted that the discharge plasma has non-uniform luminescence, which is characteristic of the non-equilibrium propagation mechanism. However, some uniformity and law of similarity in the dependence of propagation velocity on power cannot be found. This suggests that the discharge front velocity also depends in a complex way on the frequency of the heating radiation.

Note that the phenomenon of discharge propagation in inert gases in focused beams of electromagnetic waves is currently poorly studied and relevant not only in terahertz, but also in the microwave-frequency range [14,15]. In connection with this THz-discharge in inert gases is of interest not only in terms of possible practical applications, but also from the fundamental point of view.

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Conflict of interest

The authors declare that they have no conflict of interest.

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