Gas discharge sustained by powerful THz and sub-THz gyrotrons in the mixtures of noble gases with nitrogen

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Abstract. The discharge propagation velocity towards electromagnetic radiation of sub-THz and THz bands was measured in various noble gases (argon, krypton) mixtures with nitrogen in the wide pressure range (0.1 – 2 atm) for various field intensities into the focal spot (from dozen of kW/cm² to several MW/cm²). In the experimental setups two different gyrotrons were used. In case of 263 GHz it was CW gyrotron with power up 1 kW, in case of 670 GHz – pulsed gyrotron (20 µs) with power up to 40 kW. In both cases the focusing system provided the size of the focal spot of (2–3)·λ, which ensured the investigation of discharge phenomena in a wide pressure range (0.1 – 2 atm). In both cases discharge appeared in the focal spot spread towards heating radiation into the area with the field intensity much less than one in the focal spot. Velocity of the discharge propagation was measured by using photos from speed camera with small exposure (down to 20 ns) and streak camera. It was demonstrated that discharge velocity increase along with pressure decrease and drops with electric field decrease as it moves away from the focal spot.

1. Introduction

Sub-terahertz and terahertz frequency ranges still remain the least studied from the point of view of gas discharge physics. Investigation of terahertz gas discharge, sustained by the powerful focused beams of the electromagnetic radiation, has become possible recently due to the development of the powerful sources in this range (FELs and gyrotrons) [1-5] and is of interest both from a fundamental research and from possible applications. Due to the fact that the powerful sources of THz radiation have become available recently gas discharge physics in this frequency range has hardly developed in comparison with the discharge physics in nearby bands – IR and microwave.

Any gas discharge tends to spread. In the case of a laser spark, this effect was discovered and investigated in one of the very first works devoted to this type of discharge [6]. At present, it can be concluded that the phenomenon of discharge propagation in the case of a laser spark has been studied in sufficient detail (see reference 7). In the case of the microwave range, the propagation of a discharge in air has been studied in the most detail [8-9], which is connected both with the study of various ways of creating microwave plasmatrons, and with the struggle against parasitic breakdown of waveguide paths for high-power microwave radiation [8]. There are also several works devoted to the propagation of microwave discharges in noble gases both in waveguides [10-12] and in focused beams...
of microwave radiation [13-15]. It should be noted that the interest in the latter type of discharges has not weaken until now [15].

During experiments on breakdown by THz beams, it turned out that in the range pressure of the discharge exist, it changes its size, structure, and emitted spectrum. Therefore, there is the assumption that the various mechanisms responsible for the propagation of the discharge will be leading only under certain conditions.

This work presents the results of the studies of the discharge propagation under the action of the focused beam of sub-terahertz (263 GHz) and terahertz (670 GHz) gyrotrons. The discharge propagation velocity towards electromagnetic radiation was measured in various noble gases (argon, krypton) mixtures with nitrogen in the wide pressure range (0.1 – 2 atm) for various field intensities into the focal spot (from dozen of kW/cm$^2$ to several MW/cm$^2$).

2. Experimental setups

In these experiments the pulsed gyrotron (1 on figure 1) with output power 40 kW in pulse duration 20μs was used as a source of radiation at frequency 670GHz. The beam generated in gyrotron passes through the input Teflon window to vacuum chamber where focuses by quasi-optical mirror to spot with diameter close to 2λ (λ=440 μm). Maximum power density was 7 MW/cm$^2$, which corresponds to the rms electric field density 50 kV/cm.

The second experimental setup with CW 263GHz gyrotron close configuration (see figure 2). In that case in the beam waist radiation power was equal 10 kW/cm$^2$ which means 2 kV/cm rms electric field density.

![Figure 1. Experimental setup (photo): gyrotron (1), quasi-optical converter (2), discharge chamber with a window for optical diagnostics of discharge glowing (3), gas injection system (4), vacuum pumping system (5).](image1)

![Figure 2. Scheme of the 263 GHz experimental setup. 1 - gyrotron, 2 - vacuum chamber, 3 – turbomolecular pump, 4 – THz beam, 5 – focusing mirror, 6 – beam waist/discharge plasma, 7 – video camera.](image2)

The chamber construction allows working with various gases at pressure up to 2 atm. Before the experiment the chamber pumped out to a pressure 10$^{-6}$ Torr to eliminate the influence of impurities, first of all - oxygen.
In case experiment with 670 GHz gyrotron due to high density of electric field in the beam waist there was not need to set up initiators in that area so all the discharges happen in free space. In case of 263 GHz gyrotron the field intensity of 2 kV/cm is not enough for self-breakdown. In this case we used a spark discharge near the beam waist as the discharge initiator.

Discharge observation was possible through the glass flange of the chamber. Measurements could be taken by several cameras. The first was streak-camera and the second one was Nanogate-24 camera.

In the first case, studies of the discharge dynamics were carried out using an FER-27 streak-camera. The image from the streak-camera screen was recorded using a Pentax K10D camera. The scan duration of the streak-camera was regulated from 3 microseconds to 100 microseconds. Thus, it was possible to trace the propagation of the discharge in a wide range of velocities: from $10^4$ to $10^7$ cm/s.

The “Nanogate -24” is a camera from “Nanoscan” (spectral range of photocathode sensitivity 350-850 nm, number of CCD pixels 1380x1024). That camera has high-speed shutter and as a result the minimum possible frame exposure time is 20ns. Over this time plasma could spread only several millimeters or less, so we can assume that the plasma was static for one frame. Numerous photos with different delay between discharge occurrence and camera shutter were taken to calculate propagation velocity at every point along the propagation path. Discharge propagation velocity can be easily calculated as distance divided by time between adjacent frames.

In case of 263 GHz gyrotron velocity of the discharge front was much lower (in order of $10^2$ cm/s). And so for the study of discharge propagation the simple video camera with 60 fps was enough.

3. Experimental results

For the both cases (670 GHz and 263 GHz) discharge appeared at the beam waist and propagated towards heating radiation. From the figure 3 one can see the time-integrated photo of the discharge in the mixture of the argon with nitrogen. It can be seen that the structure of the discharge repeats the structure of the electric field which means the non-uniform character of the discharge propagation. Orange halo around the main part of the discharge corresponds to the first positive system of nitrogen which excited by the ultraviolet radiation from the main discharge. In case of pure argon the orange halo is absent (see figure 4).

![Figure 3](image1.png)  Photo of the 670 GHz discharge in the mixture of the argon and nitrogen (5%). Gas pressure – 0.2 atm.

![Figure 4](image2.png)  Photo of the 670 GHz discharge in the pure argon. Gas pressure – 0.1 atm.

The velocity of the discharge front propagation in gas mixture near the beam waist exceeds the sound value and decreased with the pressure increase from $5 \times 10^5$ cm/s at 0.2 atm to $2 \times 10^5$ cm/s at 1 atm. Study of the streak-camera photos demonstrated that the velocity drops with electric field decrease as it moves away from the focal spot (see figure 5). In this case, the images show two characteristic areas with different speeds (1 and 2 in Figure 5). It is assumed that the transition from one region to another is due to the fact that in this region the electric field becomes lower than the breakdown field and the propagation mechanism in the form of an ionization wave is replaced by
some other one. At the moment, it is assumed that, as in microwave discharges, the propagation mechanism is associated with ultraviolet radiation from the discharge front. It is interesting to note that the propagation velocity in a mixture of argon and nitrogen practically did not differ from the propagation velocity in pure argon, although when even a few percent of nitrogen was added, the ionization frequency dropped significantly. This circumstance currently requires further research.

Figure 5. Streak camera photo for 670 GHz discharge. Mixture of the argon with nitrogen (5%). Gas pressure – 1 atm.

In the case of a 263 GHz gyrotron, the propagation pattern changed to equilibrium, when the structure of the discharge glow repeats the temperature distribution. Figure 6 shows a photo of a discharge in a mixture of krypton and nitrogen. Heating radiation falls from top to bottom (as indicated in the setup diagram in figure 2). The discharge starts in the region of the beam waist and propagates towards the radiation. In this case, even in the region of the waist, the field is less than the breakdown one, and already a few centimeters from it, the field becomes so small that the mechanism of discharge propagation becomes equilibrium and ionization is carried out due to thermal heating of the gas. In this case, gas heating can be carried out both due to thermal conductivity (slow combustion [7]), and due to ultraviolet radiation, which creates a plasma halo ahead of the discharge front, in which heating electromagnetic radiation is absorbed [8]. The characteristic velocities of propagation were at the level of $10^2$ cm/s, which is significantly lower than the speed of sound.

Figure 6. Photo of the 263 GHz discharge in the mixture of the krypton and nitrogen. Gas pressure – 1 atm.

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