Gas breakdown in a focused beam of powerful sub-THz gyrotron

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Abstract.

The results of experimental and theoretical investigations of gas breakdown thresholds in a focused beam of powerful sub-THz radiation are presented. The gas discharge, maintained by the powerful radiation of terahertz frequency band, is a new specific object of gas discharge physics. This paper presents the experiments with pulsed gyrotron capable of generation 250 kW power at 0.25 THz frequency. The gyrotron wave beam was focused by means of quasi-optical mirrors into the spot with diameter less than 3 mm that provided intensity into the focal spot up to 3.5 MW/cm^2. Achieved electrical field intensity was enough for gas breakdown into the range of pressure values of 1-1500 Torr for various gases (argon, krypton, nitrogen, air). The boundary values of field intensity for discharge existence were measured. Noble gases data was compared to the analytical model of Raizer and Vyskrebentsev for monatomic gases.

Introduction.

The terahertz frequency range is currently the least studied from the point of view of gas discharge physics. Certain progress in the study of the discharge, sustained by the powerful radiation of the terahertz frequency range, was achieved due to the progress in the creation of powerful radiation sources in this band [1, 2].

For the first time, gas breakdown (atmospheric pressure air) in the terahertz frequency range was carried out by radiation from a submillimeter laser [3]. In this paper, it was demonstrated that for λ = 385 and 359 μm, the breakdown power density is of the order of 1 MW/cm^2, which agrees well with the results in the infrared range (CO_2 [4], Nd [5], and ruby [6] lasers) from the point of view that the breakdown intensity increases as ω^2. This scaling was also confirmed in a recent experiments in the Budker Institute for Nuclear Research on a free-electron laser (FEL) [7, 8]. Moreover, in [8] the breakdown thresholds were measured not only in air at atmospheric pressure, but also in other gases (Ar, N_2, CO_2).

Studies held at the Institute of Applied Physics (IAP RAS) since 2009 first of all connected with the creation of powerful THz gyrotrons [1]. In contrast to FEL [8] and submillimeter laser [3] THz gyrotrons allow one to investigate discharge phenomena in a single long pulse.

It should be noted that the discharge sustained by powerful submillimeter radiation differs significantly from the well-studied localized microwave discharge [9-11] and laser spark [12]. This is due to the fact that the dynamics of the discharge, when heated by electromagnetic radiation of different frequency ranges, is significantly different due to the differences in created plasma density, gas heating rate, the ratio of the wavelength and characteristic dimensions of discharge structures, etc. Thus, the terahertz discharge is a novel object of the gas discharge physics. Due to the high value of plasma density [13-15] (10^{15} – 10^{16} cm^{-3}) such a discharge can be promising, e.g. for creation of high power point-like source of extreme ultraviolet [16-17]. Thus, THz discharge is of interest both from the point of view of fundamental science and applied.

This work is a continuation of the research held in IAP RAS [13-19] on the study of a discharge sustained by high-power radiation of THz gyrotrons and is devoted to theoretical and experimental investigation of the breakdown thresholds of various gases by radiation at 250 GHz.

Experimental setup and results.

The investigations were carried out on the experimental setup, in which gyrotron generating radiation at frequency of 250 GHz was used as source of submillimeter radiation. Gyrotron, designed and created in IAP RAS in collaboration with GYCOM Ltd, provides short pulse (20 – 40 μs) regimes with a repetition rate up to 10 Hz and with a maximum output power of 250 kW@250 GHz, which could be varied smoothly by changing the magnetic field in the magnetic system of gyrotron. Radiation through quasi-optical line was directed to a pumped vacuum chamber filled with the working gas where the plasma was created (see Fig. 1). The vacuum chamber was pre-pumped to a pressure of 10^{-6} Torr to avoid the effect of the residual gas, and then the gas was injected to the required pressure. The operating pressure range was from 1 to 1500 Torr. Terahertz radiation was focused by means of quasi-optical mirror, placed into the discharge chamber, in a spot with a diameter of less than 3 mm. The maximum density of the incident power was about 3.5 MW/cm^2 that correspond to the effective field value of 30 kV/cm.

The breakdown curve was calculated based on a theory of breakdown of monatomic non-light gases in electromagnetic field with frequency ranged from RF to optical [20].

Fig.1. Experimental setup. 1 – 250kW@250 GHz gyrotron. 2 – Discharge chamber.

It should be noted that the results of calculations using this model are in good agreement with the results of experiments in the microwave range and qualitatively in the infrared [20]. Photo of the breakdown in a focused beam of terahertz waves (250 GHz) is shown in Fig. 2.

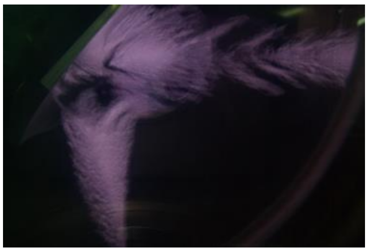

Fig.2. Discharge photo in visible band in argon (50 Torr).

Terahertz wave beam after reflection from a mirror spread from top to bottom. As one can see, the discharge spreads from the point of maximum intensity of the electric field towards the beam. Argon pressure in the discharge chamber was of 50 Torr, THz power – 250 kW. Fig. 3 shows the results of the experimental measurement of the threshold field intensity depending to the pressure in the discharge chamber (black spots) along with calculated one (blue) for argon (Fig. 3a) and krypton (Fig. 3b).

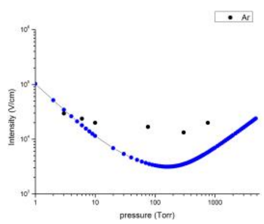

Fig. 3a. Breakdown curve for argon in case of 250 GHz heating. Black spots – experimental one, blue one – calculated.

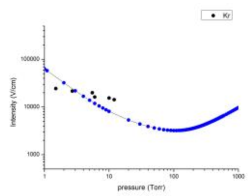

Fig. 3b. Breakdown curve for krypton in case of 250 GHz heating. Black spots – experimental one, blue one – calculated.

As one can see it is the good agreement in case of lower pressures in spite of the case of higher pressures. It can be caused by the fact that this simple theory [20] doesn't take into account elastic losses which are growing along with gas pressure value.

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