Theoretical and experimental study of THz discharge threshold in various gases.

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Abstract

In spite of the well-studied microwave discharge and laser, the discharge in the beams of the THz frequency band remains practically unexplored, including the gas breakdown threshold. The result of theoretical and experimental research of breakdown by powerful THz and sub-THz radiation of gyrotron in various gases (Ar, Kr, Xe, N_2, O_2) are presented in this work.

Experimental data were carried out in two setups. In both cases focused beams of THz emission were used. In the first setup heating radiation were provided by gyrotron working in pulsed regime and generating radiation with a frequency of 0.67 THz with power of 40 kW and maximum electric field intensity 33kV/cm. In the second setup we used gyrotron with 0.25 THz radiation frequency with power up to 250 kW and maximum intensity 28kV/cm. Discharge was studied in various gases (both for noble and molecular) in pressure range from 1 to 1500 Torr.

Calculations of breakdown threshold in heavy gases were based on Raizer discharge theory [1]. Calculation of breakdown electrical field for molecular gases (Air, N_2, O_2) provided by using previous measured and calculated values of ionization frequency and diffusion coefficient which were carried out for static electric fields by replacing it to effective electric field [2]. In calculation we supposed that electrons were heated by numerous collisions. In case of electronegative gases the electron attachment [3] and detachment [4] processes were also taken into account. In conclusion the experimental and theoretical results were compared.

Introduction

THz frequency range situated between microwave and optical frequency specter range remained almost inaccessible to researchers for a long time. Furthermore, THz frequency range is the least studied frequency range from the point of view of physics of gas discharge. While physic of microwave discharge and laser spark (in optical and IR range) was swiftly studying, there were no experiments on THz discharge at all. Nowadays there are significant progress in THz discharge research conduct with creating of powerful sources of coherent radiation in this frequency range - gyrotrons and Free Electron Lasers (FELs).

The main goal of our experiment was to experimentally get the electric field breakdown threshold dependence from the gas pressure and then compare data with curves theoretically calculated. In our experiment we used two gyrotrons working with different output radiation parameters: radiation with frequency 0.250 THz and power 250 kW in pulse duration 40 μs, radiation with frequency 0.67 THz and power 40 kW in pulse duration 40 μs.

Experiment

The work was performed on several installations, with various gyrotrons having different output radiation frequencies, however, we will provide a detailed description of only one of them. In this stand, the source of radiation was a gyrotron working in pulse regime with a maximum output radiation power of 250 kW and frequency of 0.25 THz. The scheme of the stand is shown in fig. 1.

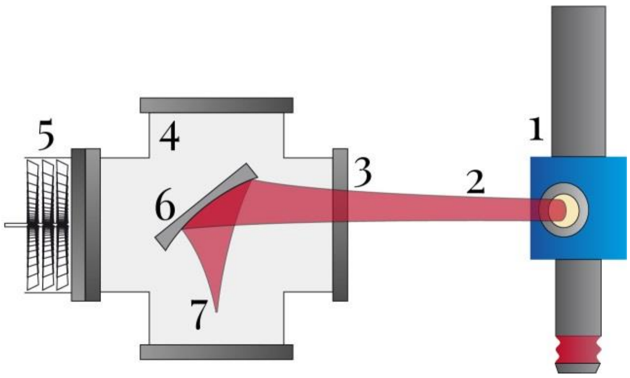

Fig.1. Scheme of the experimental setup with 0.25 THz gyrotron. 1) gyrotron 2) THz beam 3) THz enter window 4) vacuum chamber 5) turbomolecular pump 6) turning and focusing mirror 7) mirror focus.

Gyrotron radiation propagates through quasi-optical mirror system into vacuum chamber, where it is focused with the help of the mirror. The chamber was previously pumped out to pressures of the order of $10^{-5} - 10^{-6}$ Torr to eliminate the impact of residual atmosoheric gas on the breakdown conditions. After that chamber was filled with working gas.

Due to radiation absorption and refraction on low-pressure-polyethylene enter window 90% of radiation power reached to mirror focus. Also the diameter of beam waist was measured and it was equal $\approx 3\lambda$ (3.6 mm). From all of that we could estimate that the rms electric field density is 28 kV/cm in it at maximum output power radiation 250 kW. Discharge appeared in beam waist. It could be register by photodetector as well as with naked eye through the optical flange of the vacuum chamber.

The dependences of electrical field breakdown threshold on pressure were measured in the experiments and they will be shown below. Working on setup with 0.25 THz radiation there were able to vary output power of it, so the breakdown curve were obtained in wide pressure range. But since the gyrotron with frequency 0.67 THz could work only with fixed output power 40 kW in pulse regime, thus only the limits of discharge on pressure were determined.

Theory

In the easiest event, the discharge will occur if the ionization frequency (υ_i) is greater than the losses frequency is determined by the electron diffusion frequency from discharge area ($\nu_d = \frac{D}{\Lambda^2}, \Lambda -$ diffusion length), where it can not be captured by the electric field. It is called Townsend discharge condition. However, the determination of effective ionization frequency in all gases has to be calculated providing for their features.

In case of noble gas discharge we calculated breakdown curves according to Raizer theory [1] where assumes that electrons are heating on elastic collision with neutrals and electron's energy can dissipates on excitation of it. Theoretical and experimental curves shown on fig.2 and fig.3.

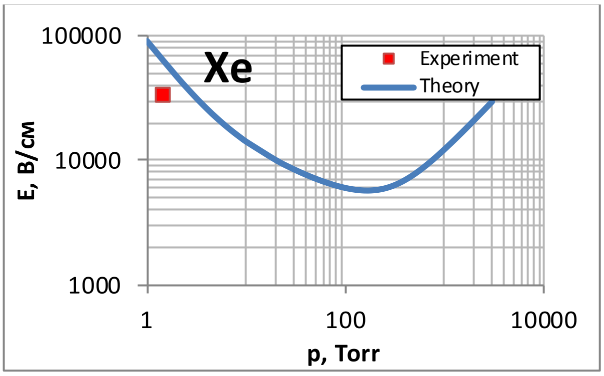

Fig. 2. Electrical field breakdown density threshold versus pressure in Xe with radiation frequency 0.67THz. Line is the result of calculation according to Raizer gas discharge theory, points – experimental result.

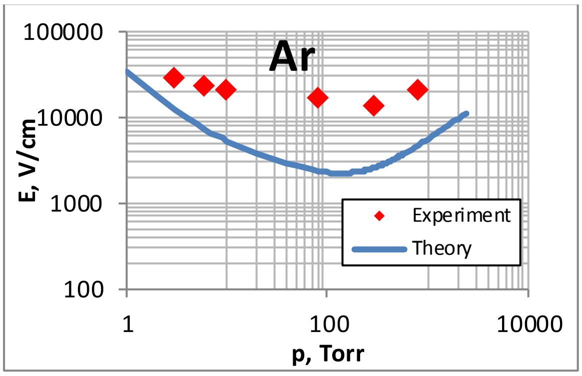

Fig. 3. Electrical field breakdown density threshold versus pressure in Ar with radiation frequency 0.25THz. Line is the result of calculation according to Raizer gas discharge theory, points – experimental results.

As it turned out the main process of electron energy losses in N_2 breakdown is the molecular vibration excitation [2]. For calculation the ionization (ν_i) and transport (ν_t) collision frequency we took their tabulated parameters depending from E/N parameter, where instead of the electric field density we took its effective value ($E_{eff}^2 = E^2 \frac{\upsilon_t^2}{\upsilon_t^2 + \omega^2}$). We solved an equation similar to the Townsend equation, but with effective ionizing and transport collisions frequencies values to receive breakdown threshold $\nu_{i\,eff}(E_{eff}, \omega) - \frac{D(E_{eff}, \omega)}{\Lambda^2} = 0$. The comparison experimental and theoretical result are shown on fig.4.

In Oxygen breakdown we cannot be limited only by taking into account the electron diffusion losses. The main mechanism of electron death is an attachment to neutrals with the formation of a negative ion [3]. Also, in the plasma there may be a reverse process - electron detachment[4]. The balance model of electron and negative ions were solved numerically to find electric field breakdown threshold. Unfortunately, due to high breakdown electric field threshold we can observe it only on setup with 0.67 THz gyrotron.

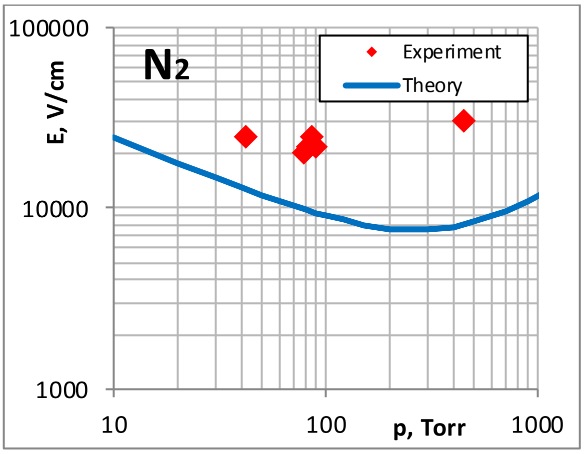

Fig. 4. Electrical field breakdown density threshold versus pressure in N_2 with radiation frequency 0.25THz. Line is a theoretically calculated curve, points – experimental results.

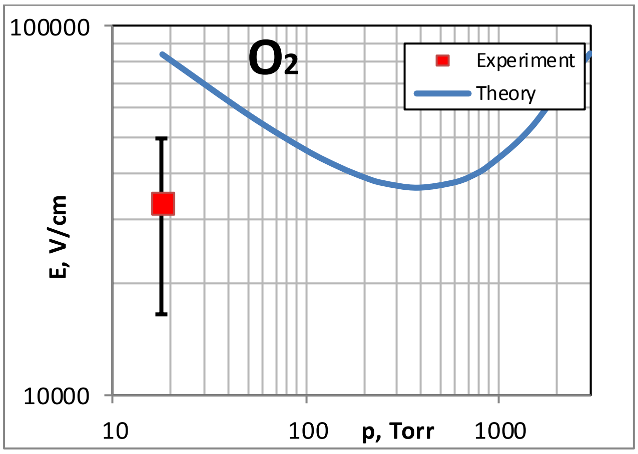

Fig. 5. Electrical field breakdown density threshold versus pressure in O_2 with radiation frequency 0.67THz. Line is a theoretically calculated curve, point – experimental result.

Discussion

Despite the roughness of some assumptions, theoretical curves show us a good agreement with experiments. Also, it is important to note that not only the values of the breakdown fields, but also the pressure value at which the minimum of the theoretical and experimental breakdown curve is reached. This confirms our assumption that exactly the effective value of the electric field is responsible for the breakdown.

Acknowledgments

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