# Plasma glow dynamics of pulsed nitrogen discharge induced by the powerful terahertz waves

A.V. Vodopyanov, M.Yu. Glyavin, A.G. Luchinin, S.V. Razin, A.V. Sidorov, A.P. Fokin
Institute of Applied Physics RAS, 46 Ulyanova str, Nizhny Novgorod, Russia

***Abstract*— We present the first results of studying a pulsed (20 μs) discharge in nitrogen, which is produced by high-power (40 kW) focused beam of terahertz (0.67 THz) waves. The time dynamics of the discharge plasma glowing is studied in a wide range of wavelengths (300–650 nm) and gas pressures (0.5–350 Torr). An assumption is made about the determining role of long-living metastables of nitrogen $N_2$ ($A^3\Sigma_u^+$) in the observed dynamics of the discharge afterglow.**

## I. Introduction

In recent years, high-power pulse gyrotrons operated in the terahertz frequency range have been developed [1, 2], which allowed one to start studying discharge phenomena in quasi-optical beams of terahertz waves. The dense plasma produced by a terahertz wave beam is a new, poorly studied subject of gas-discharge physics, therefore, this research line is of fundamental interest. The authors of several works [3-6] studied self-sustained and initiated gas breakdown and the arising discharge in focused beams of terahertz gyrotron radiation, as well as temporal and spatial features of discharge plasma glowing at various pressures and in various spectrum regions. Argon was used as the working gas in these experiments. Specifically, it was shown experimentally that such a discharge can be an high-power source of both optical, and a significantly shorter-wave radiation [5, 6], which can be of interested from the viewpoint of practical applications.

In this work, we present the results of studying a pulse discharge in nitrogen, which is produced by high-power focused beam of terahertz radiation. The conditions for discharge ignition are determined, and the dynamics of the discharge plasma glowing is studied in different spectral intervals and at different pressures.

## II. Experimental setup

The experimental setup shown in Fig. 1 was described in detail in [4]. Terahertz waves having a frequency of 0.67 THz were produced by a pulse gyrotron with a pulse duration of 20 μs. The gyrotron radiation was transformed to the Gaussian beam by means of a quasi-optical converter and focused in the discharge chamber. An additional parabolic mirror having a focal length of 0.8 mm was placed in the region of the beam waist. In the majority of the experiments, the discharge was ignited at the focal point of this mirror in a strongly inhomogeneous gas flow, which was formed by injecting gas under a pressure of up to 5.5 atm into the discharge chamber through a hole 0.15 mm in diameter, which was located in the vertex of the parabolic mirror. The power of the terahertz radiation near the gas inlet hole was equal to 40 kW. The glowing of the discharge was diagnosed using a photoelectron multiplier capable of detecting radiation in the range from 200 to 650 nm. Additionally, various optical filters were used to analyze the spectrum composition of plasma radiation, as well as a MS 5204i (SOL Instruments) monochromator having a detection range of 200 - 900 nm. The discharge chamber was preliminary evacuated with vacuum pumps down to a residual pressure of $1{\cdot}10^{-5}$ Torr, and the working pressure in the chamber ranged from $5{\cdot}10^{-3}$ to 350 Torr.

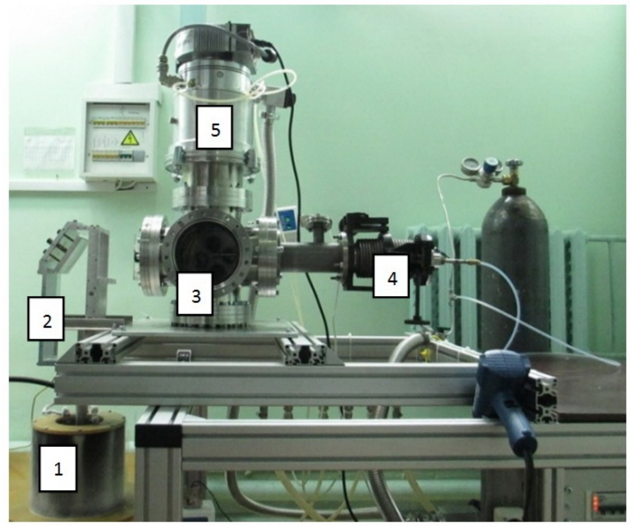


**Fig. 1.** Experimental setup (photo): gyrotron (1), quasioptical converter (2), discharge chamber with a window for optical diagnostics of discharge glowing (3), gas injection system (4), vacuum pumping system (5).

## III. Experimental results

Figure 2 shows the time-integrated photos of the discharge in the visible range in the presence of a gas flow and at different pressures of nitrogen in the discharge chamber.

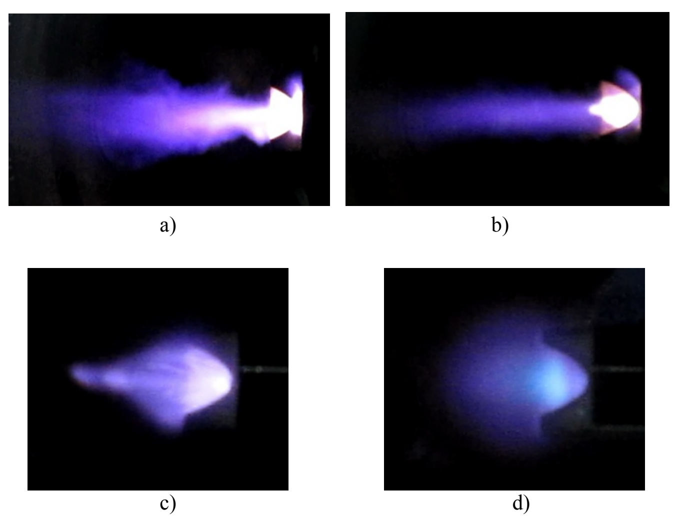


**Fig. 2.** Time-integrated photos of the discharge plasma glowing in the gas flow in the visible range at different pressures of nitrogen in the discharge chamber: a) 100 Torr, b) 53 Torr, c) 12 Torr, and d) 0.5 Torr.

It is seen from the presented photos that the size of the discharge glowing decreases with a decrease in the gas pressure in the chamber. This is due to the fact that at relatively low pressures, the breakdown conditions are fulfilled only in a small region of space near the gas inlet hole. (It should be noted that a similar pattern was observed earlier in a terahertz discharge in argon (see [4, 6])). In the presence of a gas flow, the discharge was ignited at pressures in the chamber exceeding 0.2 Torr, whereas in static gas, the discharge was produced at pressures exceeding 12 Torr.

The experiments studying the dynamics of the glowing of the discharge plasma demonstrated that at relatively high pressures (over 50 Torr), a long (with a duration of about 1–1.5 ms) afterglow exists after the end of the terahertz pulse, and the afterglow intensity can exceed the intensity of the plasma glowing during the pulse significantly, by several times (see Fig. 3, curve 1). At pressures below 50 Torr, the afterglow duration turns to be significantly shorter being about 100 µs. In this case, the dynamics of the afterglow turns to be significantly different as well, specifically, the photomultiplier signal decreases monotonically (see curve 2 in Fig. 3). It should be noted that the afterglow with different time scales and different dynamics was observed in [5, 6] in a terahertz discharge in argon plasma. However, in nitrogen, by contrast with argon, long afterglow is observed at high gas pressures.

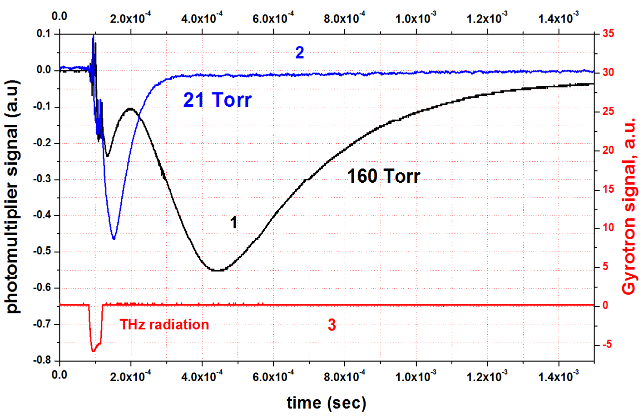


**Fig. 3.** The waveforms. Curve 1 is photomultiplier signal in the spectral range of 300-400 nm, the gas pressure was 160 Torr. Curve 2 is photomultiplier signal in the spectral range of 300-650 nm, the gas pressure was 21 Torr. Curve 3 is heating pulse of terahertz waves.

Spectroscopic studies with the use of optical filters showed that the long afterglow lies in the UV spectral range, i.e., in the range from approximately 300 to 400 nm, where intense radiation of the second positive system of nitrogen ($C^3\Pi_u \rightarrow B^3\Pi_g$) is possible. A shorter afterglow lies in a considerably wider spectra region, approximately from 300 to 650 nm.

Deeper studies using the MS 5204i monochromator demonstrated that long nonmonotonic glowing is produced by the vibrational bands 0→1 (λ = 357.7 nm), 4→7 (λ = 385.8 nm) and 3→7 (λ = 414.2 nm) of the second positive system of nitrogen. At the same time, radiation of the vibrational bands 0→0 (λ = 337.1 nm), 1→2 (λ = 353.7 nm) and 0→4 (λ = 434.4 nm) does not produce an afterglow that is that long.

As of now, the kinetics of the processes leading to the observed experimental facts has not been studied yet. However, basing on the literature data (see, e.g., [7-9]), one can make the following assumptions. Under certain conditions, long-living nitrogen metastables in the $A^3\Sigma_u^+$ state are produced efficiently in the nitrogen discharge and its afterglow as a result of certain processes (e.g., such as $N_2(X^1\Sigma_g^+) + e \rightarrow N_2(A^3\Sigma_u^+) + e$; $N(^4S) + N(^4S) + N_2(X^1\Sigma_g^+) \rightarrow N_2(A^3\Sigma_u^+) + N_2(X^1\Sigma_g^+)$; $N(^2P) + N_2(X^1\Sigma_g^+, v \geq 10) \rightarrow N_2(A^3\Sigma_u^+) + N(^4S)$ and other processes). As a result of reactions with participation of these metastables, specifically, in the reaction $N_2(A^3\Sigma_u^+) + N_2(A^3\Sigma_u^+) \rightarrow N_2(C^3\Pi_u) + N_2(X^1\Sigma_g^+)$ the electron level $C^3\Pi_u$ is populated, and its luminescence results in a long afterglow. However, detailed explanation of the observed dynamics of the discharge plasma glowing requires further investigation.

## IV. Summary

This works presents the results of studying a pulsed discharge in nitrogen, which is produced by focused beam of terahertz radiation. The conditions for discharge ignition have been determined experimentally, and the dynamics of the discharge plasma glowing has been studied in the wavelength range from 300 to 650 nm and the pressure range from 0.5 to 350 Torr. We observed a long-time (up to 1.5 ms) nonmonotonic intense afterglow in some vibrational bands of the second positive system of nitrogen. An assumption is made that the main role in the observed dynamics of the discharge afterglow is played by long-living metastables of nitrogen $N_2(A^3\Sigma_u^+)$.

This work was supported by the Russian Foundation for Basic Research, project #13-02-01407.

## References

[1] V.L. Bratman, M.Yu. Glyavin, Yu.K. Kalynov, A.G. Litvak, A.G. Luchinin, A.V. Savilov, V.E. Zapevalov, "Terahertz Gyrotrons at IAP RAS: Status and New Designs", *Int. J. IRMM&THz Waves*, v. 32, p. 371-379, 2011.

[2] M.Yu Glyavin, A.G. Luchinin, G.S. Nusinovich, J. Rodgers, D.G. Kashyn, C.A. Romero-Talamas, R. Pu, "A 670 GHz gyrotron with record power and efficiency", *Applied Physics Letters*, v. 101, p. 153503, 2012.

[3] V.L. Bratman, V.G. Zorin, Yu.K. Kalynov, V.A. Koldanov, A.G. Litvak, S.V. Razin, A.V. Sidorov, and V.A. Skalyga, "Plasma creation by terahertz electromagnetic radiation", *Physics of plasmas*, v. 18, p. 083507, 2011.

[4] M.Yu. Glyavin, S.V. Golubev, V.G. Zorin, I.V. Izotov, A.G. Litvak, A.G. Luchinin, M.V. Morozkin, S.V. Razin, A.V. Sidorov, V.A. Skalyga, "The discharge maintained by high-power terahertz radiation in a nonuniform gas flow", *Radiophysics and Quantum Electronics*, v. 56, n. 8-9, p. 561 - 565, 2014.

[5] V. L. Bratman, I. V. Izotov, Yu. K. Kalynov, V. A. Koldanov, A. G. Litvak, S. V. Razin, A. V. Sidorov, V. A. Skalyga, V. G. Zorin, "Features of the plasma glow in the low pressure terahertz gas discharge", *Physics of Plasmas*, v. 20, p. 123512, 2013.

[6] M.Yu. Glyavin, S.V. Golubev, I.V. Izotov, A.G. Litvak, A.G. Luchinin, S.V. Razin, A.V. Sidorov, V.A. Skalyga, and A.V. Vodopyanov, "A point-like source of extreme ultraviolet radiation based on a discharge in a non-uniform gas flow, sustained by powerful gyrotron radiation of terahertz frequency band", *Applied Physics Letters*, v. 105, p. 174101, 2014.

[7] D.I. Slovetskii, *Mechanisms of chemical reactions in non-equilibrium plasma,* Moscow, Nauka, 1980 (in Russian).

[8] N.A. Bogatov, M.S. Gitlin, S.V. Golubev, S.V. Razin, "Investigation of relaxation of metastable $N_2(A^3\Sigma_u^+)$ molecules after a pulsed discharge in nitrogen", *Abstracts of 9th European Sectional Conf. on the Atomic and Molecular Physics of Ionized Gases (ESCAMPIG)*, v. 12H, p. 79-80, Lisbon, Portugal, 1988.

[9] J. Henriques, E. Tatarova, F.M. Dias, C.M. Ferreira, "Spatial structure of slot-antenna excited microwave $N_2$ – Ar plasma source", *Journal of Applied Physics*, v. 103, p. 103304, 2008.