04.1

Features of the breakdown in heavy noble gases under the action of Novosibirsk free electron laser radiation

© A.V. Sidorov[1], A.P. Veselov[1], A.V. Vodopyanov[1], V.V. Kubarev[2], Ya.I. Gorbachev[2], O.A. Shevchenko[2]

[1] Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia
[2] Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
E-mail: alexsv@ipfran.ru

Received November 11, 2022
Revised November 28, 2022
Accepted November 29, 2022

The results of experimental studies on the breakdown of noble gases (argon and krypton) by terahertz radiation from the Novosibirsk free electron laser (NovoFEL) are presented. For the first time, the breakdown thresholds of noble gases by terahertz radiation were measured in a wide pressure range (0.2–1.5 bar). Previous experiments to measure breakdown thresholds in the THz range in various gases were carried out for hundreds of GHz or at atmospheric pressure. Experimental breakdown thresholds are compared with calculated data using various simplified models.

Keywords: THz radiation, gas breakdown, THz laser discharge.

DOI: 10.21883/TPL.2023.02.55362.19424

The terahertz (THz) radiation range is currently receiving a lot of research attention, since it appears well-suited for a broad spectrum of fundamental and applied studies in physics and other fields. The relatively recent progress in design of power THz radiation sources (free electron lasers and gyrotrons) [1–5] opened up the opportunities for examination of discharge phenomena in this frequency range.

Dense plasma of a THz discharge may be used as an intense source of ultraviolet radiation operating at frequencies extending through to extreme UV (EUV) [6]. The typical plasma density of a THz discharge falls within the range of $10^{16}-3\cdot10^{17}\,\mathrm{cm}^{-3}$. This density interval was demonstrated to be the optimum one in terms of radiation efficiency in the EUV range [7].

The first THz breakdown was induced in atmospheric-pressure air by radiation of a D_2O laser at a wavelength of $385\,\mu$m [8]. The authors of that study did not examine the breakdown phenomena in detail. The thresholds of breakdown of heavy noble gases by THz radiation were measured in [9,10]. It was noted that the obtained data agree well with the results of calculations performed in accordance with the model of breakdown of heavy noble gases [11] for low pressures. The same was not true in the region of high pressures, where the mismatch between measurements and calculations was apparently attributable to elastic losses that are neglected in [11] and increase with gas pressure.

An in-depth experimental study of breakdown of various atmospheric gases (argon included) under atmospheric pressure was performed at the Novosibirsk free electron laser (NovoFEL) [12]. The present study is focused on the experimental and theoretical examination of breakdown thresholds of heavy noble gases (krypton and argon) within a wide pressure range at the focused NovoFEL beam [1]. The breakdown thresholds were measured at a specially designed experimental station [13]. The obtained experimental results were compared with calculated data.

The complete optical circuit of the station for these experiments is presented in Fig. 1. NovoFEL radiation *2* (reflected off parabolic mirror *3* from open-type radiation transport channel *1* was introduced into discharge chamber *4* through mirror *5* that was made of synthetic CVD diamond and positioned at Brewster's angle in the focal beam waist beyond mirror *3*. The optical system in the discharge chamber, which featured two parabolic mirrors *6*, *7*, focused NovoFEL radiation to a spot on plane mirror *8* with a minimum transverse size (the width at half intensity of a Gaussian NovoFEL beam with a wavelength of $130\,\mu$m was around 0.3 mm). This allowed us to observe breakdown phenomena under significantly suboptimal pressures [12]. The repetition rate in a continuous train of NovoFEL radiation pulses was 5.6 MHz. The FWHM of a single pulse was approximately 100 ps. As was demonstrated in [12], the breakdown factor is the integral of intensity over the pulse duration or the pulse energy density, which is proportional to the mean NovoFEL power. The mean NovoFEL power could be reduced continuously by increasing a slight $(10^{-4}-10^{-5})$ negative detuning of the repetition rate of electron pulses relative to the circulation rate of an intracavity THz light pulse. All NovoFEL radiation parameters were monitored at a specialized metrology station. The gas pressure at which breakdown occurred in the pre-evacuated chamber was identified by continuous variation for each altered (reduced) value of the mean NovoFEL power. The emergence of glow visible to the naked eye and recorded by detectors was assumed to signify breakdown (inset in Fig. 1).

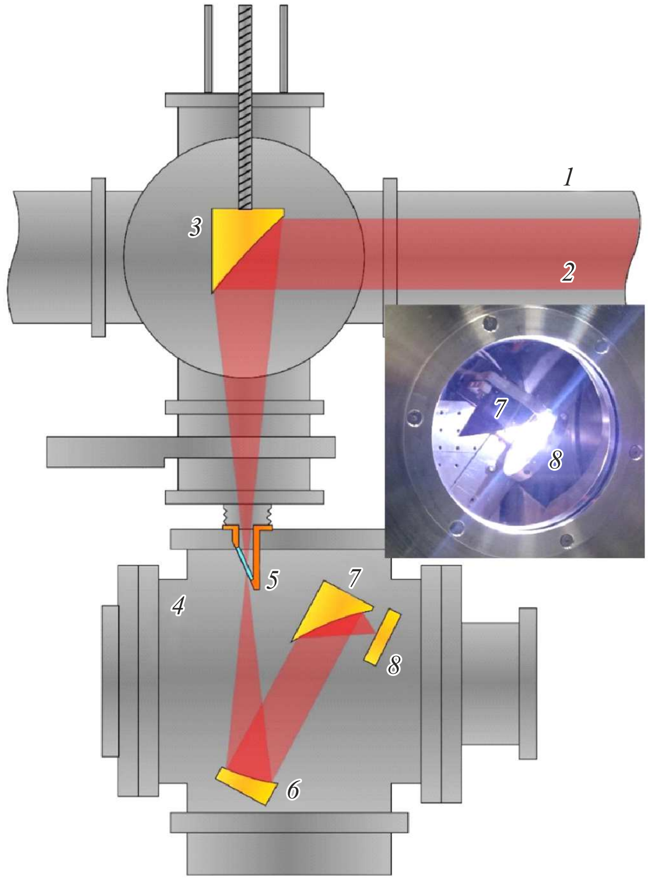

Figure 1. Optical circuit of the station for laser discharge experiments. Explanations are given in the text. An example photographic image of a discharge in argon after breakdown is shown in the inset.

Experimental dependences of the breakdown electric field intensity on pressure are presented in Fig. 2. The minimum breakdown pressure was 0.4 bar for argon and 0.2 bar for krypton at a mean NovoFEL radiation power of 160−170 W (the maximum values in the present series of experiments). Unfortunately, we could not measure breakdown fields for the so-called „right branch" of the breakdown curve in the experiment, since this required pressures up to 5 bar. The maximum gas pressure in our discharge chamber was limited by the mechanical properties of the input diamond window and was set to 1.5 bar. However, the rightmost points of the experimental dependences are close to the minimum breakdown fields (especially for krypton; see theoretical dependences below). The curve for krypton reaches its minimum at lower pressures than the curve for argon, since the rate of electron–atom collisions in krypton is higher at equal gas pressures.

Figure 2 also presents a comparison between the experimental results and theoretical calculations. These calculations were performed in accordance with the model detailed in [12]. As was already noted, breakdown fields in heavy noble gases were calculated in [9,10] in accordance with the model proposed in [11]. A simple approximate theory of avalanche breakdown in electrics fields of arbitrary frequency (from low to optical frequencies) was advanced in this study, which relies on the concepts and approximations from [14]. It is assumed that the excitation of neutral atoms is the primary channel of energy loss of electrons in the process of their heating in the field of an electromagnetic wave. The comparison between experimental and calculated data in [11] reveals a fine agreement in the microwave range and a qualitative agreement in the IR range. The results of experiments in [9,10] also agree closely with the model proposed in [11].

Apart from the radiation frequency, the present study differs from [9,10] in that NovoFEL pulses are considerably shorter (~ 100 ps, while the pulse duration in [9,10] was on the order of several tens of microseconds). A non-steady breakdown criterion [15] needs to be used in these conditions, and it is absolutely necessary to forgo the limit (central to the model from [11]) on the maximum electron energy gained in the radiation field. The breakdown fields for these short pulses are fairly intense (1 MV/cm or higher) even under an optimum gas pressure. The electron energy loss for excitation of neutral atoms may be neglected in this case. Indeed, an electron gains an energy on the order of 1 eV in a single collision with neutral atoms. Subjected to stochastic heating [15], an electron then „slips" fairly rapidly through the dangerous section of the energy scale where the cross section of excitation of a neutral atom exceeds considerably the cross section of its ionization. The ionization rate may thus be expressed as the reciprocal time of heating of an electron to an energy at which the ionization probability becomes equal to unity [12]. This calculation for atmospheric-pressure argon was performed in [12]. In the present study, calculations were carried out both for argon and for krypton within an extended pressure interval corresponding to the range where breakdowns were observed experimentally (0.2−1.5 bar). The classical expression, which corresponds to stochastic electron heating in an AC electromagnetic field [15], was used for the dependence of breakdown voltages on pressure:

$$E(P) \sim \left[\nu_{tr}/\left(\omega^2 + \nu_{tr}^2(P)\right)\right]^{1/2},$$

where $\nu_{tr}(P) = n_0\langle\sigma_{tr}(v_e)v_e\rangle \sim P$ is the mean rate of transport collisions of electrons with neutral atoms, n_0 is the density of atoms, $\sigma_{tr}(v_e)$ is the cross section of transport collisions, v_e is the electron velocity, and $\omega = 14.5$ THz is the angular frequency of electromagnetic radiation. The values of mean rate of transport collisions under a pressure of 1 bar were used in calculations: $\nu_{tr}^{\mathrm{Ar}}(1\,\mathrm{bar}) = 6.8$ THz, $\nu_{tr}^{\mathrm{Kr}}(1\,\mathrm{bar}) = 8.3$ THz. It can be seen from Fig. 2 that the calculated data agree fairly well with the experimental results. This proves that the assumed negligible excitation loss, which distinguishes the present study from earlier ones [9,10] (where excitation losses played a major role due to a significantly slower heating of electrons), is valid.

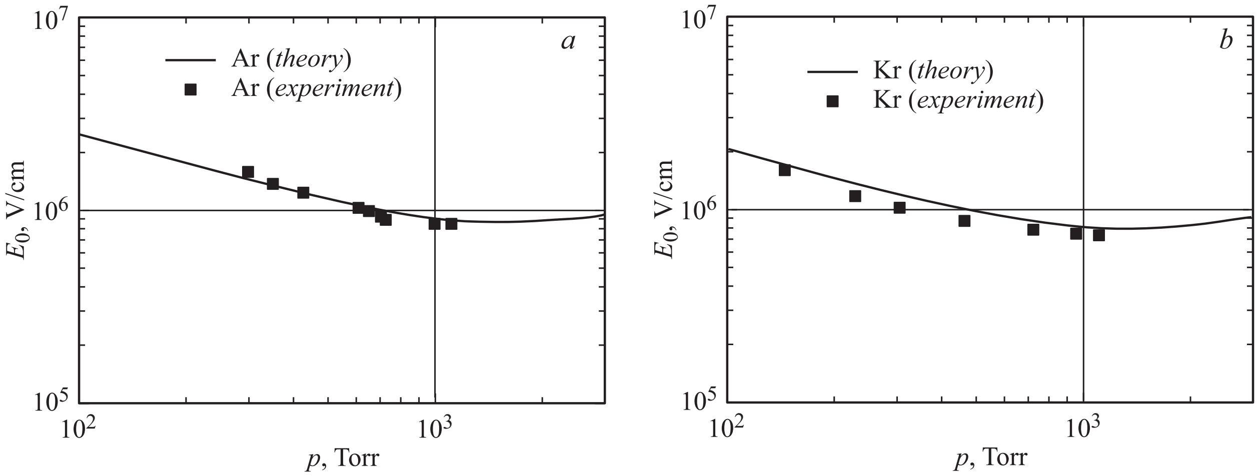

Figure 2. Dependences of the breakdown electric field intensity in argon (a) and krypton (b) on pressure for a radiation wavelength of 130 μm.

Funding

This study was supported by grant No 19-72-20166 from the Russian Science Foundation.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] V.P. Bolotin, B.A. Knyazev, E.I. Kolobanov, V.V. Kotenkov, V.V. Kubarev, G.N. Kulipanov, A.N. Matveenko, L.E. Medvedev, A.D. Oreshkov, B.Z. Persov, V.M. Popik, T.V. Salikova, S.S. Serednyakov, O.A. Shevchenko, M.A. Scheglov, N.A. Vinokurov, in *Proc. Int. Conf. IRMMW-THz-2005* (Williamsburg, USA, 2005), p. 126–127. DOI: 10.1109/ICIMW.2005.1572440

[2] G.N. Kulipanov, E.G. Bagryanskaya, E.N. Chesnokov, Yu.Yu. Choporova, V.V. Gerasimov, Ya.V. Getmanov, S.L. Kiselev, B.A. Knyazev, V.V. Kubarev, S.E. Peltek, V.M. Popik, T.V. Salikova, M.A. Scheglov, S.S. Seredniakov, O.A. Shevchenko, A.N. Skrinsky, S.L. Veber, N.A. Vinokurov, IEEE Trans. Terahertz Sci. Technol., **5**, 798 (2015). DOI: 10.1109/TTHZ.2015.2453121

[3] G.G. Denisov, M.Yu. Glyavin, A.P. Fokin, A.N. Kuftin, A.I. Tsvetkov, A.S. Sedov, E.A. Soluyanova, M.I. Bakulin, E.V. Sokolov, E.M. Tai, M.V. Morozkin, M.D. Proyavin, V.E. Zapevalov, Rev. Sci. Instrum., **89**, 084702 (2018). DOI: 10.1063/1.5040242

[4] M.Y. Glyavin, A.V. Chirkov, G.G. Denisov, A.P. Fokin, V.V. Kholoptsev, A.N. Kuftin, A.G. Luchinin, G.Yu. Golubyatnikov, V.I. Malygin, M.V. Morozkin, V.N. Manuilov, M.D. Proyavin, A.S. Sedov, E.V. Sokolov, E.M. Tai, A.I. Tsvetkov, V.E. Zapevalov, Rev. Sci. Instrum., **86**, 054705 (2015). DOI: 10.1063/1.4921322

[5] M.Yu. Glyavin, A.G. Luchinin, G.S. Nusinovich, J. Rodgers, D.G. Kashyn, C.A. Romero-Talamas, R. Pu, Appl. Phys. Lett., **101**, 153503 (2012). DOI: 10.1063/1.4757290

[6] A.G. Shalashov, A.V. Vodopyanov, I.S. Abramov, A.V. Sidorov, E.D. Gospodchikov, S.V. Razin, N.I. Chkhalo, N.N. Salashchenko, M.Yu. Glyavin, S.V. Golubev, Appl. Phys. Lett., **113** 153502 (2018). DOI: 10.1063/1.5049126

[7] I.S. Abramov, E.D. Gospodchikov, A.G. Shalashov, Phys. Rev. Appl., **10**, 034065 (2018). DOI: 10.1103/PhysRevApplied.10.034065

[8] P. Woskoboinikow, W.J. Mulligan, H.C. Praddaude, D.R. Cohn, Appl. Phys. Lett., **32**, 527 (1978). DOI: 10.1063/1.90116

[9] A.V. Sidorov, S.V. Golubev, S.V. Razin, A.P. Veselov, A.V. Vodopyanov, A.P. Fokin, A.G. Luchinin, M.Yu. Glyavin, J. Phys. D: Appl. Phys., **51**, 464002 (2018). DOI: 10.1088/1361-6463/aadb3c

[10] A. Sidorov, S. Razin, A. Veselov, A. Vodopyanov, M. Morozkin, M. Glyavin, Phys. Plasmas, **26**, 083510 (2019). DOI: 10.1063/1.5109526

[11] A.I. Vyskrebentsev, Yu.P. Raizer, J. Appl. Mech. Tech. Phys., **14**, 32 (1973). DOI: 10.1007/BF00850574.

[12] V.V. Kubarev, Ya.V. Getmanov, O.A. Shevchenko, P.V. Koshlyakov, J. Infrared. Millimeter Terahertz Waves, **38**, 787 (2017). DOI: 10.1007/s10762-017-0380-3

[13] V.V. Kubarev, G.I. Sozinov, M.A. Scheglov, A.V. Vodopyanov, A.V. Sidorov, A.R. Melnikov, S.I. Veber, IEEE Trans. Terahertz Sci. Technol., **10**, 634 (2020). DOI: 10.1109/TTHZ.2020.3010046

[14] Ya.B. Zel'dovich, Yu.P. Raizer, Sov. Phys. JETP, **20**, 779 (1965).

[15] Yu.P. Raizer, *Gas discharge physics* (Springer, N.Y., 1991).