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Discharge of heavy noble gases induced by pulsed gyrotron radiation with 1 THz frequency

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In this work, gas discharge ignited by girotron radiation with frequency 1 THz was carried out. Breakdown curves were calculated both for selfignited and initiated discharges. There was shown that in a case of breakdown by the pulse radiation with duration longer than several microseconds electric field threshold is the same as in a case of continuous wave breakdown. Also, the possibility of using a terahertz gyrotron as a radiation source for discharge in gas targets on installations for extreme ultraviolet photolithography was assessed.

Keywords: girotron, terahertz breakdown, extreme ultraviolet lithography.

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The terahertz (THz) range of frequencies of electromagnetic waves, which is located between microwave and infrared spectral regions, has long remained the least utilized and has been regarded as too short-wave for the methods of classical vacuum electronics and too low-frequency for quantum electronics techniques. At the same time, this range has several specific features that make it rather appealing for various avenues of fundamental and applied research in physics, chemistry, biology, and medicine [1]. Studies into a gas discharge sustained by THz radiation, which have become feasible only relatively recently due to the progress in fabrication of high-power sources of such radiation [2,3], are of special interest.

The results of these studies of a gas discharge in a new frequency range are of academic interest and have practical implications. For example, a discharge in a nonuniform flow of heavy inert gases sustained by high-power THz radiation may serve as an efficient source of ultraviolet (including vacuum (VUV) and extreme (EUV) ultraviolet) radiation. This is due to the fact that the plasma density (the cut-off density) expected in a THz discharge falls within the $10^{16}-10^{17}\,cm^{-3}$ range, which is the optimum one in terms of plasma emissivity in the EUV range [4]. In addition, THz radiation wavelengths are comparable to the characteristic discharge size, thus providing closer coupling between plasma and heating electromagnetic radiation [5]. The results of studies published to date reveal the feasibility of this concept [6] and demonstrate that frequencies of heating radiation at the level of $1-3$ THz [6] are needed to raise the efficiency of EUV emission.

Free-electron lasers (FELs) [2] and large-orbit gyrotrons [7] are the most intense sources of the indicated frequency range available at present. Specifically, the maximum radiation power provided by a gyrotron operating at a frequency of 1 THz was 400 W [7]. Several updated designs of this gyrotron aimed at raising the power of radiation with a frequency of 1 THz to $1-2$ kW have already been proposed [8].

The prospects for application of this gyrotron as a source for producing a point discharge in a nonuniform gas flow have been examined in [9]. It has been demonstrated that kilowatt-level power is sufficient to produce a discharge in heavy inert gases if this discharge is initiated by generating pre-plasma (e.g., with a spark discharge). However, the so-called steady-state breakdown criterion [10] was used in [9] to probe the evolution of an electron avalanche.

In the present study, we examine the evolution of an initiated discharge sustained by radiation with a frequency of 1 THz with account for the finite length of a heating radiation pulse. The pulse parameters at which the steady-state criterion is applicable were determined.

Heavy inert gases (argon, krypton, and xenon) were chosen to be used as the primary gases for breakdown and the production of a VUV radiation source. An electron heated in an oscillating field to the ionization energy collides with neutral atoms and, since the mass of an atom is large, does not lose energy in these collisions. In fact, excitation potentials are close to the ionization ones for monoatomic gases and assume values on the order of ten volts; therefore, electron collisions in the process of heating may be considered to be largely elastic, and excitation losses may be neglected. Non-steady-state Raizer breakdown criterion $\nu_i - \nu_d = \ln(n_{crit}/n_0)/\tau$, where ν_i is the ionization rate, ν_d is the diffusion rate, n_0 is the initial plasma concentration, n_{crit} is the end concentration, and τ is the pulse length [11], may be used in this case to characterize the breakdown.

In the case of breakdown by long pulses, the right-hand side of this equation may be neglected. One then obtains steady-state breakdown criterion $\nu_i = \nu_d = D/\Lambda^2$,

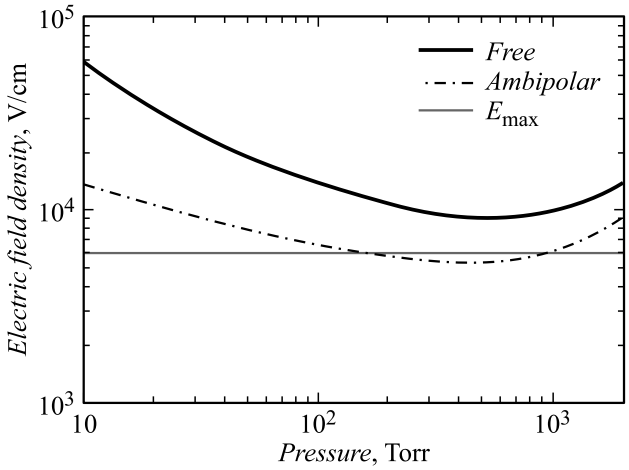

Figure 1. Dependences of the threshold field of breakdown by continuous radiation with a frequency of 1 THz on gas (argon) pressure for the cases of free and ambipolar diffusion. The horizontal line denotes the maximum possible field at the waist of a radiation beam with diameter $3\lambda = 0.9$ mm and a power of 400 W at a frequency of 1 THz.

where D is the diffusion coefficient and Λ is the diffusion length. Only the diffusion losses of electrons are taken into account here. Since the size of a THz discharge is on the order of a millimeter, electron losses are significant. The radiation power may be insufficient to produce a discharge. The rate of electron losses needs to be reduced to facilitate breakdown. This may be achieved by altering the diffusion type. It has been demonstrated that a spark discharge present in the vicinity of a discharge region induces the formation of ions and seed electrons. It gets harder for electrons to leave the discharge region (the charge-separation field restrains them). The diffusion mechanism shifts from free diffusion to the ambipolar one. It can be seen from Fig. 1 that this change in the nature of diffusion leads to a considerable suppression of the threshold breakdown field throughout the entire pressure range.

In the case of ultrashort pulses, the term associated with ν_d on the left-hand side of the non-steady-state breakdown criterion may be neglected. Electric breakdown field E is then specified exclusively by the pulse length, since $\nu_i \propto E^2 \propto 1/\tau$. Such behavior was observed in studies focused on FEL breakdown, where the pulse length was on the order of several tens of picoseconds [2].

The threshold breakdown field for the above-discussed gyrotron with a radiation frequency of 1 THz was calculated for a pulse length of 8 μs. Breakdown curves for other pulse lengths were also plotted.

It can be seen from Fig. 2 that the threshold breakdown field increases by a factor lower than 1.2 as the pulse length changes by an order of magnitude; i.e., the threshold field intensity depends only weakly on the pulse length. This implies that the electron escape is governed exclusively by diffusion losses in the discharge region. It has been demonstrated earlier [12] that the power of an electromagnetic wave of the gigahertz frequency range may be increased by introducing it into an open three-mirror cavity with a reflecting diffraction grating on one mirror acting as a coupler. A 30-fold power enhancement has been achieved experimentally in [12]. It follows as a logical consequence that a breakdown may also be initiated with a radiation source with a pulse length of 8 μs by compressing the pulse by a factor of 2–4: this should result in a 1.4–2-fold enhancement of the maximum field at the waist, while the threshold breakdown field will remain essentially unchanged.

Since the gyrotron radiation power is fairly low, a breakdown may be facilitated in several ways. Figure 3 presents the results of calculation of the breakdown curve for both free and ambipolar diffusion types with the gyrotron pulse length taken into account. It is evident that a breakdown in gas (argon) may be initiated in a beam field with double the intensity; in the case of ambipolar diffusion, a breakdown is possible even in the pressure range of background gas (from several tens to a thousand Torr).

Thus, breakdown curves in heavy inert gases under the influence of heating radiation with a THz frequency were examined in a wide pressure range using the results of calculations relying on the Raizer breakdown theory. It is worth noting that the mechanisms of diffusion losses of electrons and restrictions related to the length of a heating radiation pulse are central to the determination of the threshold breakdown field in heavy gases. In the case of breakdown in the vicinity of pre-plasma, the diffusion type change (from free diffusion to the ambipolar one), which lowers the breakdown field intensity and facilitates breakdown, plays a significant part in reducing the electron losses. It was demonstrated that pulse compression may also facilitate breakdown due to the enhancement of the local electric beam field. This is made possible by the fact that the electric field at the beam waist increases under compression in inverse proportion to the root of the pulse

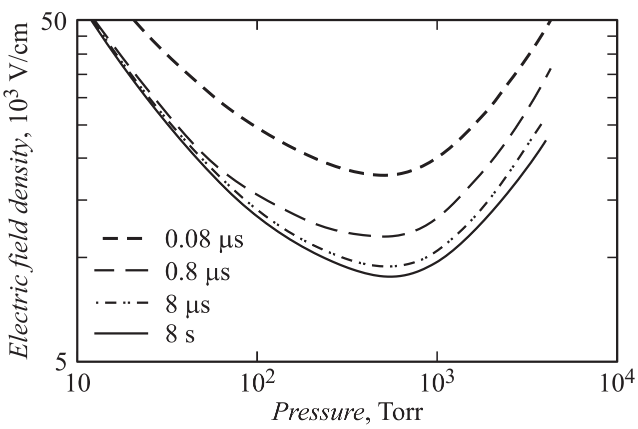

Figure 2. Dependences of the threshold field of breakdown by pulsed radiation with a frequency of 1 THz on gas (argon) pressure for heating radiation pulses of various length.

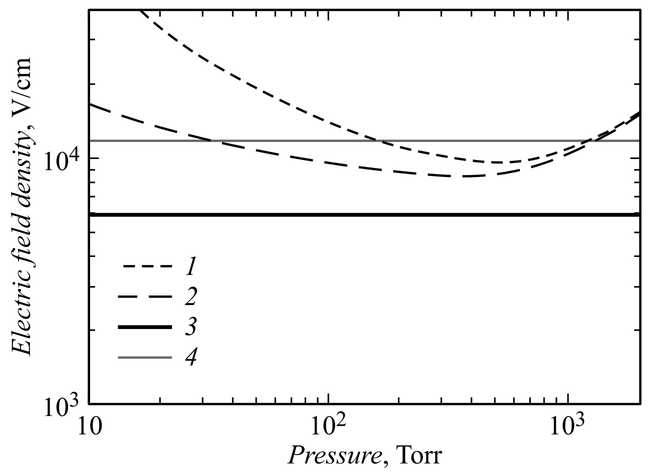

Figure 3. Dependences of the threshold breakdown field on gas (argon) pressure for heating radiation with a frequency of 1 THz at the following diffusion and pulse lengths: *1* — $\tau = 8\,\mu$s, $\Lambda = 0.15$ mm; *2* — $\tau = 8\,\mu$s, $\Lambda = 1.5$ mm; *3* — maximum possible field at the beam waist of a gyrotron with diameter $3\lambda = 0.9$ mm, a power of 400 W, and a frequency of 1 THz; *4* — doubled value of the maximum possible beam field.

length, while the threshold breakdown field remains almost unchanged in the case of long pulses.

The results of calculations reveal that a power in excess of 1 kW is needed to induce a breakdown in heavy inert gases within a relatively wide pressure range in a real-world experiment with pulsed gyrotron radiation. Applying the breakdown facilitation techniques, one may then also initiate a discharge in a nonuniform gas jet and examine the plasma glow in UV, VUV, and EUV ranges. This power level appears to be within the reach of modern large-orbit gyrotrons. In fact, it will soon be demonstrated experimentally [8].

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Conflict of interest

The authors declare that they have no conflict of interest.

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